

THE "CULLINAN" DIAMOND

The rough stone (below) and the nine larger cut gems
(Photographs of glass models. $\frac{2}{3}$ actual size)

A KEY TO PRECIOUS STONES

BY

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PREFACE

Precious stones or gem-stones are mineral products, and this book, written by a mineralogist, deals with them from a mineralogical point of view. Their serious study is a branch of scientific mineralogy, and there is much more in them than what merely catches the eye. Their determination and naming can be correctly done only with some knowledge of the principles of mineralogy. This of course involves the use of some technical terms, but very nearly all those here used will be found in *The Concise Oxford Dictionary*—and this cannot be said of all the “technical” expressions used in sports and fashions. Minerals of different kinds must be given names, and these names often have a more precise meaning than the names of people. An attempt has been made to give in popular language a general account of the properties and composition of gem-stones, where they are found in the earth’s crust, and to what uses they can be put. Romance and mystery and feelings of æsthetic rapture, often associated with gem-stones, are kept in the background. Prominence is given to hard facts, and the driest (but really the most important) of these are assembled at the end of each chapter as key tables for purposes of reference. Many books have been written on precious stones;

but the basic literature is to be found in the textbooks and treatises on mineralogy and widely scattered in many scientific periodicals. The standard work on the subject is the late Professor Max Bauer's *Edelsteinkunde* (Leipzig, 1896), of which I gave an English translation *Precious Stones* (London, 1904, now out of print); a third German edition has been prepared by Professor Karl Schlossmacher (Leipzig, 1928-32). A trade journal on popular lines is *The Gemmologist*, published monthly in London. Useful guide-books to collections are issued by the Geological Survey and Museum, the Victoria and Albert Museum, and the Imperial Institute, all at South Kensington. Many of the examples referred to in the text and some of the specimens figured are in the mineral collection of the British Museum of Natural History, also at South Kensington.

NOTE TO SECOND EDITION

A few minor revisions and additions have been made without alteration of the pagination. For a revision of some of the optical data in the tables I am much indebted to Mr. B. W. Anderson and Mr. C. J. Payne of the Laboratory of the Diamond, Pearl and Precious Stone Trade Section of the London Chamber of Commerce, where numerous precise determinations have been made on minerals of gem quality.

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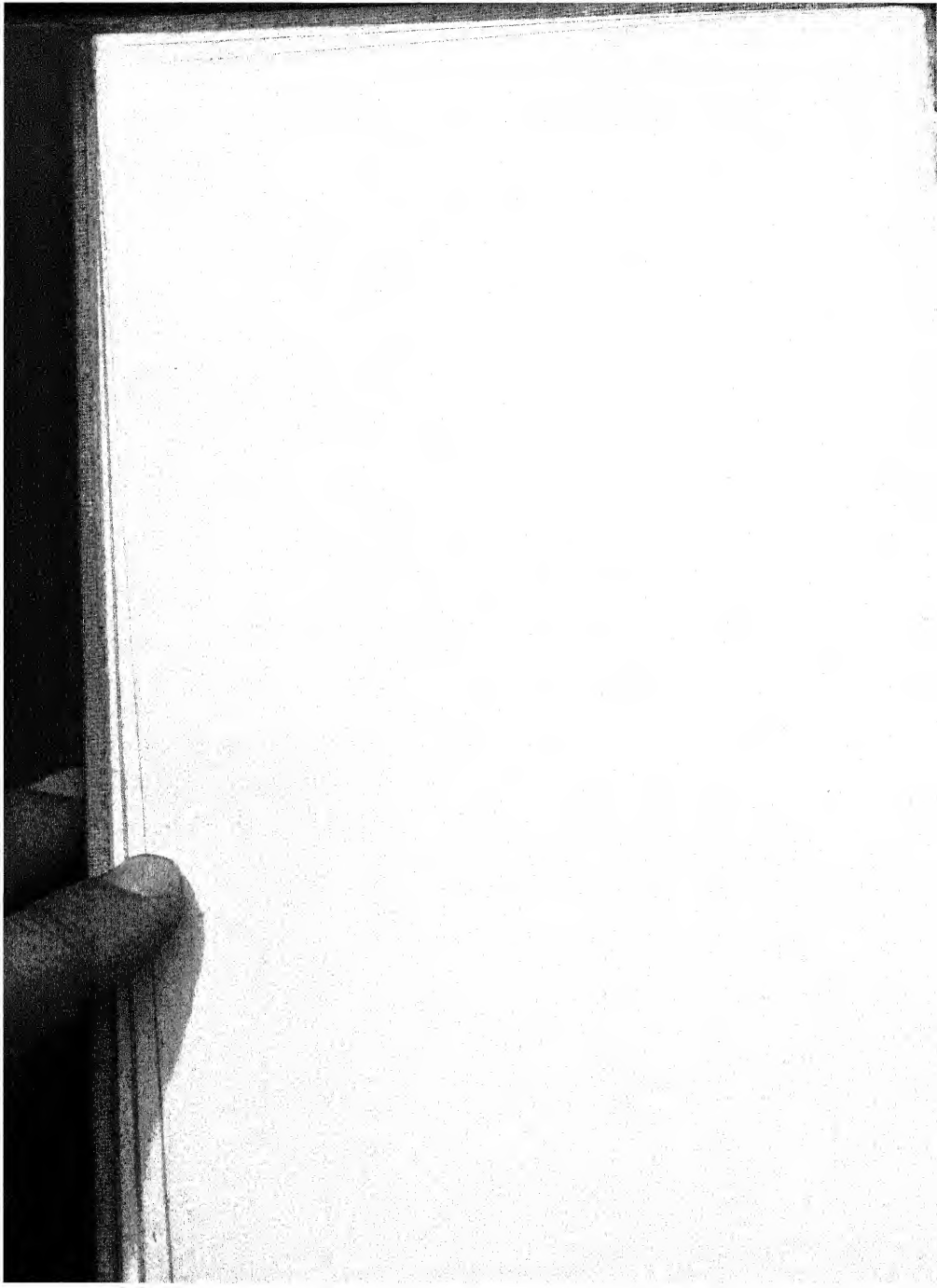
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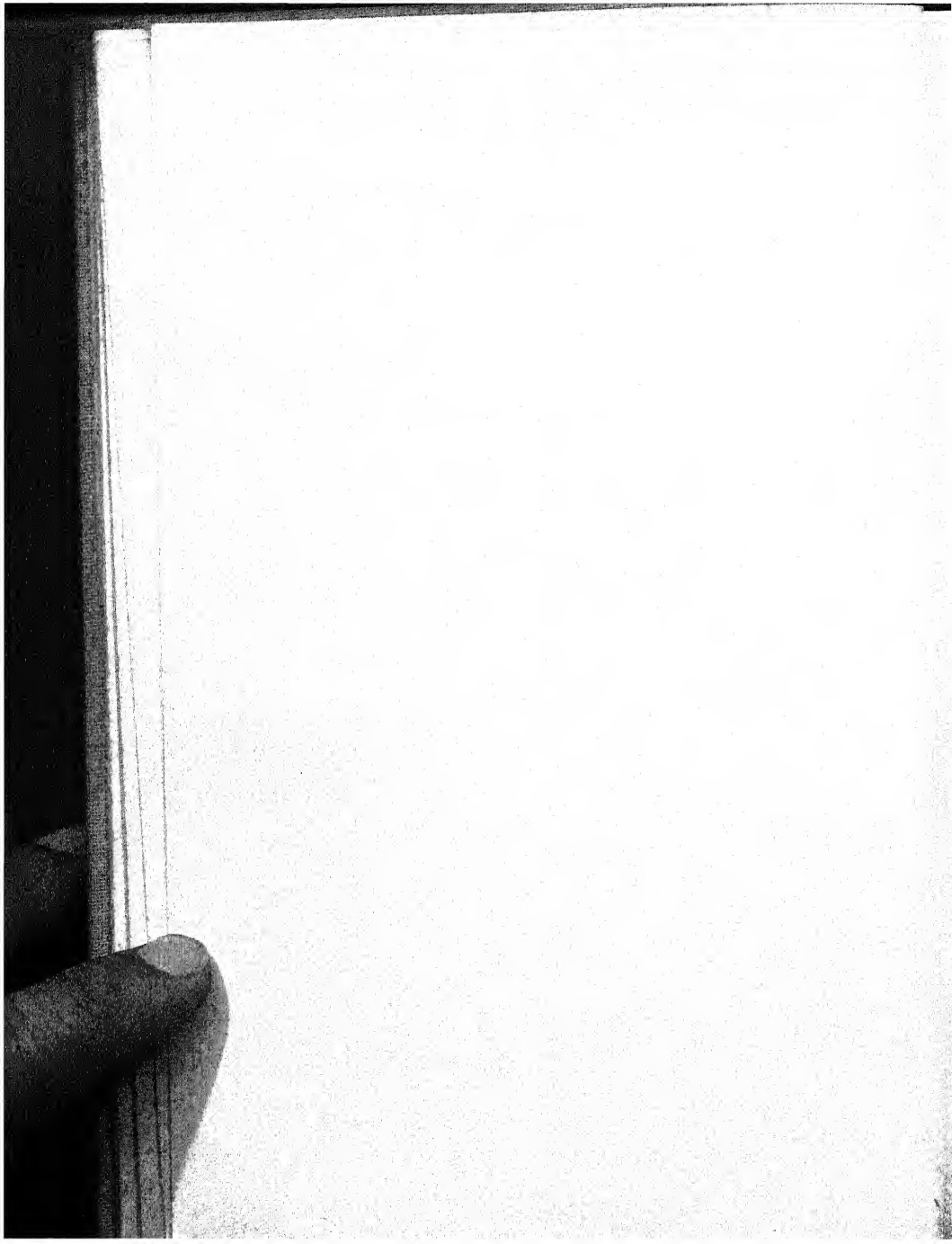
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PART I
GENERAL PRINCIPLES



CHAPTER I

Introduction

PRECIOUS stones may be regarded as the flowers of the Mineral Kingdom, flowers that do not fade, but with a lasting and permanent value. With their bright colours and brilliant lustre they immediately attract attention. But these qualities are fully brought out only when the stones are suitably cut and mounted. A rough stone or pebble is quite unattractive in appearance and would be passed over by most people. The casual admirer of gems, whose horizon is limited to diamond, ruby, sapphire, emerald, and opal, really sees no more in them than in bits of tinsel and coloured glass, and is only duly impressed when told that they are very rare and costly. If precious stones attracted attention only on account of their gaudiness and costliness, then there would be little more to say about them beyond the merely obvious. They possess, however, a number of remarkable properties which can only be appreciated and understood when they are studied more closely.

Animal, vegetable, or mineral? Pearls, coral, and ivory are animal products, amber and jet are vegetable products, and these can scarcely be regarded as stones. All other gem materials of natural origin are mineral products. These are hard stones, and are at once distinguished by their hardness from the much softer materials of animal and vegetable origin. It is this high degree of hardness that enables these stones to be worn as personal ornaments without deterioration. We could then define a precious stone as any mineral

which by reason of its colour and lustre is attractive in appearance, and which at the same time possesses a degree of hardness sufficient to withstand wear. There are several common minerals to which such a definition would apply; but being common and plentiful the adjective "precious" seems scarcely appropriate. Such stones are usually classed as semi-precious stones, while "precious" stones are those that are really rare and hard to get.

Such distinctions are, however, quite arbitrary. The best quality of ruby and emerald are now rare and difficult to obtain, and are therefore regarded with favour and classed as precious stones of the first rank. But supposing that to-morrow new deposits of these stones were found in large amount, and that all known deposits of, say, amethyst became exhausted, then no doubt the latter would come into favour and there would be an interchange in rank. Several new occurrences of diamond have been discovered during recent years, but the market is controlled by powerful combines and large stocks are held in reserve; the rank of diamond as a precious stone and its high price are thus maintained. The transformation of coal into petrol is now an accomplished process, and undoubtedly some day in the future it will be possible to produce diamond from coal (often popularly called "black diamond"). It would then be possible to use diamond for many technical purposes on account of its very high degree of hardness; then perhaps diamond would be despised as an ornamental stone. During the past thirty years crystallized corundum of fine gem quality and with a wide range of attractive colours has been produced in large quantities by artificial means. Strenuous efforts are naturally made by the trade to keep out these products from competition with native ruby and sapphire under the false pretence that they are not real and genuine.

If we are to regard scarcity as of such importance, there

are several minerals unknown to jewellers that could be used as precious stones, but which are known only as very few specimens, or only a single one, preserved in mineral collections. The science of mineralogy is a progressive one and new minerals are constantly being found. With the discovery and opening up of new mineral deposits in many of the regions of the world as yet unprospected, it is very probable that several new precious stones are yet to be discovered. The horizon of the jeweller will then no longer be confined to diamond, ruby, sapphire, emerald, and opal. We live in a progressive age.

Since precious stones are minerals, they must be seriously studied as minerals. They are not merely pretty things only to look at. Some acquaintance with the general principles of mineralogy is therefore necessary for the proper appreciation of precious stones. About half of the present book is therefore devoted to a popular and elementary exposition of such general principles so far as they apply to precious stones. Without this preliminary account the succeeding descriptive chapters dealing with the several kinds of precious stones would perhaps not always be quite intelligible. We do not wish to confine the descriptive portion to such statements as the following: Ruby is red, it is rare and costly, and is found in Burma. Old King Cole had a ruby valued at £x in his crown.

We must aim at something more than this in scientific mineralogy. The work of the mineralogist is to find out all about the different kinds of minerals that enter into the composition of the earth's crust, and to study their distribution and modes of occurrence and origin. In order to do this it is first necessary to determine the characters of each kind or species of mineral and to arrange the several species in some order of classification. These are simple minerals. The study of rocks, consisting of mixtures of simple minerals, is left to the petrologist; but these are the matrix in which precious stones have

grown. The limits of some mineral species are not yet clearly defined, though there is no doubt about the common and well-known minerals that provide gem-stones. For example, the species diamond, corundum, quartz, beryl, topaz, &c., are each well and clearly defined, and they include as colour or gem varieties ruby, sapphire, amethyst, citrine, emerald, aquamarine, &c. About 1200 well-defined mineral species are known, and about fifty of these minerals have been cut and polished as gem-stones. Each of these minerals has grown as a number of single individual crystals, and it is only a few of the most perfect individuals from a vast crowd that are suitable for gem purposes—just as in the human species certain individuals stand out in prominence.

The accurate determination of the characters of all the different mineral species is a matter of some importance. The data so accumulated as constants for each species can then be used when determining the nature of an unknown stone. Gem-stones belonging to different mineral species are often very similar in appearance, especially when their essential characters are obscured by cutting and mounting as gems. They can only safely be distinguished with certainty by determining one or more of these essential characters by special tests. As an example, powdered salt and sugar cannot be distinguished by sight, and the simple test of taste is applied. If we had a crystal of salt and a crystal of sugar we should at once see the difference between them. The idea that jewellers can distinguish cut gems at sight is fallacious. They very frequently make mistakes in naming the mineral species, and when presented with something unusual they make wild shots. Lists of the essential characters of the mineral species used as gem-stones are given at the end of each of the following chapters. It is believed that these will be more useful than penny-in-the-slot determinative tables based on colour.

Most books on precious stones include some mention of values and prices. It is, however, safer to avoid any mention of definite prices, since these vary enormously not only with quality of the stones, but also with the characters of the seller and the buyer. Prices are quite fictitious, and it is a case of get what you can. Rough corundum as mined for abrasive purposes fetches at the mines about £10 per ton, while quite small stones of gem quality are sold by the carat (five million metric carats to the metric ton of 2205 lb.), and for stones of exceptional quality the price demanded may range from £100 to £1000 per carat (i.e. $£5 \times 10^9$ per ton, which rather reduces the matter to an absurdity). These are clearly luxury goods. A whole handful of the best rubies would be of no use whatever to a man on a desert island.

CHAPTER II

Colour, Lustre, and Brilliancy

COLOUR, lustre, and brilliancy are the features that immediately attract attention to gem-stones, and it is entirely on these characters that the beauty of the stones depends. They appeal merely to the sense of sight. But on account of their rarity and costliness, they may also raise feelings of proud possession or of envy. Except for show, they are really of little use. A red stone may be a ruby, blue a sapphire, green an emerald, yellow a topaz, whilst colourless ones flashing fire may be diamond or only "paste", and not so good as Lady Snookes's diamonds. That is all the ordinary person can say by merely looking at the things.

Colour is really very deceptive. It all depends on the light and on the degree of colour-vision or blindness of the observer. In the dark, no colour is to be seen. Colours, as we know them, have to be seen in *white* light. Viewed in yellow light, a ruby is black and a diamond is yellow. The colour we see really depends on the kind of light which is illuminating the object under observation. The white light of the sun, as everybody knows, is a mixture of all the colours of the rainbow or the visible spectrum, in the order: red, orange, yellow, green, blue, indigo, violet (remembered as—read over your good book inversely). Light waves are of just the same nature and travel with the same speed (186,000 miles a second) as radio-waves or "wireless" waves (light waves are also "wireless"), only they are very much shorter and with correspondingly higher

frequencies or cycles. The wave-length of dark-red light is 0.0008 millimetre or 0.0000008 metre (about 30,000 waves to an inch), as compared with the English national broadcasting wave-length of 1500 metres, which is nearly two thousand million times longer. The wave-length of violet light is half that of red light—an octave higher. This octave of waves visible to human eyes is only one of the known sixty-four octaves of waves of a similar nature. Below the red, we have the infra-red or heat waves and radio-waves, and beyond the violet, the ultra-violet, X-rays, and γ -rays. In the octave of visible rays, rubies show up red and emeralds green; what they do in radio-waves and X-rays of other octaves we cannot see. A person endowed with supernatural limits of vision might see some really remarkable features in gem-stones. Why rubies are red in white light is that, for some reason, they possess the power of absorbing rays of all colours except the red, leaving these to be scattered from the surface of the stone.

The colours of gem-stones are certainly quite attractive, but in the majority of cases they are accidental and are not essential characters of the stone. Most gem minerals when in a perfectly pure state are devoid of colour. Cotton is white and silk nearly so, but fabrics of these materials can be made to look very attractive and showy by the application of dyes of various kinds, usually aniline dyes. The dye is present in only very small amount, and it does not change the character of the material, only its colour and appearance. Ordinary window glass is colourless, but stained glass windows are not uncommon. A wide range of excellent colours is produced in glass used for ornamental purposes and for making imitation gems. Here the colouring matter consists of various metallic oxides in quite small amounts melted with the glass. In manufactured gem corundum and spinel, wonderful colours have been produced by the addition of small amounts

of various metallic oxides, some of which are not found in the natural stones.

Some few gem-stones do possess a colour of their own. For example, diopase is always a rich green, this colour being due to the copper which is an essential constituent of the stone. Turquoise also owes its colour to the presence of copper in appreciable amount. Lapis-lazuli can only be blue, and at one time it was the only source of the pigment ultramarine, then of high value but now manufactured commercially. Uvarovite or chrome-garnet owes its green colour to chromium which is here present as an essential constituent of the mineral. The red, brown, and green colours of other garnets are due to the presence of iron in large amount; but a garnet containing no iron or chromium may be colourless. Hämatite also has a colour of its own, best seen when the mineral is powdered; this is like dried blood, hence the name, meaning "bloodstone" (but distinct from the variety of chalcedony now known as bloodstone). The green colour of many silicate gem minerals, such as olivine, diopside, epidote, idocrase, nephrite, is due to the presence of ferrous iron, which enters in small but variable amounts into the composition of the stones and is not present as a foreign impurity.

The "dilute" colouring or dyeing of glass and artificial corundum gems by the addition of very small amounts of metallic oxides suggests that the colouring of many gem-stones may be due to the same cause. The green colour of emerald (in otherwise colourless beryl) and the red colour of ruby (in colourless corundum) are both definitely due to the presence of chromium; the marked difference between green and red being due to the chemical state of combination of the chromium. There are, however, many cases in which the nature of the colouring matter is not yet known. Chemical analysis, and especially spectroscopic analysis, may reveal the presence of mere traces of various

elements, but to which of these, or what combination of them, the colour is due cannot be decided with certainty.

The curious changes in colour which some gem-stones may undergo when they are subjected to special treatment suggest that the coloration is, after all, not due to the presence of any pigment. We might inquire why the sky is such a beautiful blue colour, comparable with that of the sapphire; why on a foggy day the sun is ruby-red; or why we see emerald-green and other gorgeous colours at sunset. These colours surely cannot be due to the presence of any pigment in the sky. They are really due to the scattering of light by fine particles, particles of a size comparable with the wave-length of light. High up in the atmosphere, where these particles of dust and water vapour are finer, the shorter wave-lengths are scattered and we see blue; with larger particles in a fog we see red. The colour seen depends on the size of the particles or their degree of dispersion. A theory which finds much favour at the present time is that coloured crystals contain colloidal particles, either of some foreign material or of the material of the crystal itself, and that the colour seen depends on the size of these particles. A curious case is given by rock-salt, which is rarely found as violet, sky-blue, or indigo coloured crystals. When these crystals are heated, the colour disappears, but it can be restored by exposure to radium. Further, colourless rock-salt, when subjected to great pressure, becomes yellow and if then exposed to radium it turns blue. We have only to change the size of the colloidal particles and we can get just what colour we wish. Some gem-stones are amenable to such treatment, and in this direction developments may be expected in the future.

Some very interesting and puzzling changes in the colour of gem-stones have long been known. The yellow topaz from Brazil becomes a fine rosy-pink

when heated; whilst brownish-yellow topaz from Siberia and Utah is completely decolorized on prolonged exposure to sunlight. Amethyst becomes yellow when heated (and is then, shame to say, often sold as "topaz"). Diamond when exposed to radium becomes green. Certain zircons can actually be seen to be changing in colour when exposed to bright sunlight; and the original colour is slowly restored in the dark or more quickly by slightly warming the stone. This quite suggests a conjuring trick affecting the size of minute particles.

Mistaken and even stupid ideas about the colour of gem-stones are many. A very common impression is that the characteristic colour of topaz is yellow—if a stone is not yellow, it cannot be topaz, and if it is yellow, then it is topaz! This sherry-yellow topaz is known from only a single locality in Brazil, and has never been found anywhere else in the world. But most topaz from other localities in Brazil is quite colourless; some is blue and rarely green or red—quite a wide range in colours. The Brazilian yellow topaz was fashionable in early Victorian jewellery, but yellow quartz (citrine) could very easily be substituted for it by unscrupulous dealers and taken by ignorant purchasers. Even at the present day, yellow quartz passes as "Occidental topaz", "Spanish topaz", "Scotch topaz", &c., and often in the trade, dropping the qualifying adjective, as "topaz". There is no relation between the minerals quartz and topaz, and yellow is not a typical colour for topaz. It is high time that this deceptive nonsense was stopped.

Many textbooks on precious stones give determinative tables based on colour. We have seen that colour is not an essential character and that a colourless material may be dyed any colour. Such tables are futile, and will be quite misleading when we have to deal with material from a newly discovered locality or an entirely new kind of gem-stone. Further, parti-coloured

crystals showing a zoning of colour are not uncommon amongst minerals. We may have a crystal of corundum red at one end and blue at the other, i.e. both ruby and sapphire at the same time. Zonal growths in crystals marked out by bands of different colours are well shown by tourmaline. These zones of colour indicate that different impurities, taken up as colouring matter, were present in the mother-liquor at various periods of the crystal's growth.

Colour-filters are sometimes useful for distinguishing different kinds of stones that may be similar in colour, especially when a large series of mounted gems has to be examined quickly. When viewed through suitable coloured screens, different stones will appear of different colours. The reason for this is that the absorption spectra of the different stones are generally not the same, even although the stones appear to be of the same colour to the unaided eye. The colour actually seen is really a mixture of colours of different wave-lengths: in ruby not red of one wave-length, but reds of many different wave-lengths, and also a small proportion of blue. When the light that has passed through a transparent stone is examined in the spectroscope, dark bands of varying width are seen in the spectrum, corresponding to the colours that are cut out or absorbed by the stone. These absorption spectra, which generally vary for different minerals, will, of course, vary in one and the same mineral when this is of different colours or even when it is of the same apparent colour but owes that colour to different causes.

Many other interesting colour effects are displayed by gem-stones. Some of these will be mentioned in the optical chapter or under the particular minerals (opal, moonstone, alexandrite, labradorite, &c.). One that has been much studied during recent years may be mentioned here. When ruby or red spinel is exposed in a dark room to the ultra-violet rays, the stones glow

with a wonderful red light. For some curious reason, as yet unknown, they are acting as transformers of the wave-length. The short ultra-violet waves are transformed into the longer waves of red light. When a handful of diamonds is held in front of an ultra-violet lamp (the same as a hospital sunlight lamp fitted with a dark screen to cut out the visible rays) the effect is really surprising: some stones shine out with a soft cornflower-blue light and one or two may glow with a soft yellowish-green colour. This curious phenomenon is known as fluorescence, having been first observed in fluorspar or fluorite. Certain crystals of fluorite when viewed by transmitted light, by holding them up in front of a window, show a pale-brown, pink, or green colour; but when viewed by reflected light, with the observer's back towards the window, a rich bluish-violet glow or shimmer is seen over the surface of the crystal, very much like the bloom on a ripe plum. This is best seen in direct sunlight, because then more ultra-violet rays are falling on the crystal.

Much more could be said on the colour of gemstones, but we must not forget lustre and brilliancy. Of lustre there are different kinds or qualities. Adamantine lustre is characteristic of diamond, hence the name. This cannot be described in words: it must be seen, and it enables diamonds to be recognized at a glance whatever may be their colour. The surface of some rough opaque diamonds may, however, show a sub-metallic lustre. Some other minerals with a high index of refraction also show an adamantine lustre, e.g. cassiterite and rutile. Hämatite shows a sub-metallic lustre, and that of opaque metals is typically metallic. The commonest type of lustre is vitreous, like that of glass, e.g. quartz and most of the silicate minerals. The lustre of corundum and zircon lies between adamantine and vitreous, corresponding with their rather high refractive index. Pearly lustre, typical of pearls and mother-of-pearl, depends on a

fine platy structure, and may be seen on the cleavage surfaces of euclase and fibrolite. Silky lustre is shown by materials with a finely fibrous structure, e.g. cat's-eye. A resinous lustre is shown by amber and some garnets; a waxy lustre by some opals; and a greasy lustre by elæolite (a name meaning oil-stone), a stone that has occasionally been cut as a gem. Apart from kinds of lustre, we may have degrees of lustre, depending largely on the smoothness of the surface and the state of aggregation of the material. A clear colourless crystal of calcite with smooth faces shows a brilliant vitreous lustre, but a rough opaque crystal or a lump of chalk is quite dull. Lustre is, however, of importance, and with experience it is a much safer guide for "spotting" minerals than is colour.

The brilliancy of precious stones is brought out by the processes of cutting and polishing. The rough stone may be a dull pebble, but when cut it is a brilliant gem. The brilliancy of a gem depends on several factors—the transparency or clearness of the stone, the kind and degree of its lustre, and on the fineness of the polish. A harder stone will as a rule take a finer polish than a softer one; and a stone with a higher refractive index will possess greater lustre and brilliancy. For these reasons diamond takes first place in brilliancy, and in the trade diamonds are often referred to as "brilliants".

It is useless to give at the end of this chapter a reference table of the colours of gem-stones. Under red we can list almandine garnet, under green diopside and uvarovite garnet, and under blue lapis-lazuli. While under the headings red, yellow, green, blue, violet would be given merely a repetition of the names of every other kind of gem-stone. Though all such colours may not yet be known for any one particular stone, there is no reason why they should not be found to-morrow.

CHAPTER III

Density and Hardness: Heaviness and Durability

DENSITY is a measure of the amount of matter contained in a given volume or space. According to the modern electronic theory of matter, atoms consist of electrons (particles of electricity) revolving in orbits around a central nucleus. The structure of an atom has been compared with that of the solar system, the electrons corresponding with the planets and the nucleus with the sun. Or we might compare it with grains of mustard seed, each in its own orbit in a one-way traffic, revolving round a pea in the middle of Piccadilly Circus. Compared with the sizes of these bodies, the distances between them are enormous. The density of the earth as a whole is 5.5, and that of the gaseous sun only 1.4; but the density of the solar system taken as a whole must be very small indeed. Now supposing that these enormous vacant spaces in the atoms themselves and also the spaces between the billions upon billions of atoms (see fig. 3, p. 29) could be eliminated, we should then have much matter in little space. The condensation would be vastly greater than in condensed milk. A quite small gem constructed on these principles might weigh perhaps hundreds of tons (with a correspondingly high specific gravity). Such a gem would indeed be a unique and priceless possession, but surely a burden to the wearer.

The density or specific gravity of a gem-stone is of no consequence as concerns its appearance or use.

There is no connexion between the appearance of a stone and its weight, apart, of course, from size. From experience, however, we usually regard a metal or metallic mineral to be heavier than a stony one. But it is rather surprising that corundum (ruby, specific gravity 4.0) is considerably heavier than the metal (aluminium, specific gravity 2.6) of which it is essentially composed (53%). Any additional weight in a gem owing to a higher specific gravity can be of no inconvenience to the wearer. Gems are sold by weight, so much per carat, and it is not safe to make even a rough estimate of the weight of a stone from its size, unless we are quite sure what kind of stone it is. Different stones vary widely in specific gravity. For example, a zircon is much smaller than an emerald of equal weight; and a ten-carat citrine (yellow quartz) is bigger than a ten-carat topaz.

Specific gravity is, however, a character of considerable importance. With certain exceptions it has a constant value for each mineral species. It is an important and characteristic constant for each kind of mineral. A simple test of the specific gravity will usually decide at once what kind of stone we have in hand, or distinguish two stones which are identical in appearance.

The specific gravity of a substance is a measure of its weight compared with the weight of an equal volume of water, water at 4° C. (its maximum density) being taken as the standard and as unity. The metric system of weights was based on the weight of a certain volume of water, one cubic centimetre of water at 4° C. fixing the value of the one-gram weight. The specific gravity or density of a substance can then be expressed by the weight in grams of one cubic centimetre of the substance. But it would scarcely be a convenient method to cut a stone into a cube of exactly one centimetre edge for the purpose of determining the weight of one cubic centimetre.

Various methods are available for the determination of specific gravity. The one most generally applicable is that of hydrostatic weighing. The body is first weighed in air and then in water. It will be found to weigh less in water, because of buoyancy. The difference is in fact the weight of the displaced water. A body of specific gravity 1 will have no weight in water, and will remain suspended in the liquid, neither sinking nor floating. The difference between the two weighings thus gives the weight of a volume of water equal to that of the stone. If, for example, the weight in air is 4 (grams, ounces, or pounds), and that in water is 3 (in the same units of weight), then the weight of an equal volume of water will be 1. The stone is thus four times as heavy as water and its specific gravity is 4, a value indicating that we are dealing with corundum. Expressed generally, if a is the weight in air and w the weight in water, then $a - w$ is the weight of an equal volume of water, and $\frac{a}{a - w}$ is the value of the specific gravity.

The experiment will of course be made at room-temperature, say 15° C. (= 59° F.). At this temperature water has a density of 0.999160, and the body is less buoyed up than in water at 4° C.; w will be greater, and consequently $a - w$ less, and $\frac{a}{a - w}$ greater. A correction must therefore be made by deducting some small amount from the determined value. In the example given above this would be 0.007, so that the true value is 3.993. With a stone of lower specific gravity the correction is less (for quartz about 0.004), but with heavier substances and increasing temperature it mounts up (for gold at 30° C. the correction is 0.11). However, this correction can usually be neglected, and certainly can the more refined corrections dealing with the buoyancy in air of the stone and of the weights used. For all practical purposes a

specific gravity stated to two places of decimals is quite sufficient. But in dividing a by $a - w$ the division sum is sometimes foolishly continued to four or five places of decimals.

Since gem-stones, especially when cut, are rather small, it is necessary to use a rather delicate balance (fig. 1) weighing to at least one milligram (0.005 carat). The value w may be quite small, and the suspending

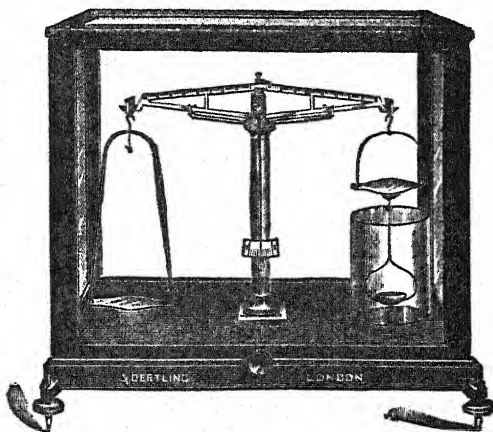


Fig. 1.—Balance for hydrostatic weighing in determining the specific gravity of gem-stones

wire in the water acts as a drag on the balance. The stone is suspended by a very thin wire or hair (thread sucks up the water) and held in a wire loop or basket. The weight in water of this arrangement must be determined separately, and the amount deducted from the weight when the stone is in place completely immersed in the water. Another important precaution is to remove any adhering bubbles of air, as these add considerably to the buoyancy. This can best be done with a fine camel-hair brush.

Other weighing methods for the determination of specific gravity are with the pycnometer, Westphal's

balance, Jolly's spring balance, or hydrometer. A form of pycnometer suitable for use with gem-stones is simply a small wide-necked bottle or tube covered with a plate of ground glass. But all these take time with the weighing and subsequent little calculation. A much quicker method is with the use of heavy liquids—a suspension method. A block of wood floats on water and a block of iron sinks. The specific gravity of wood is less than that of water, whilst that of iron is greater. (Iron ships float because they are hollow and displace the same weight of water as their own weight.) Most stones also sink in water, but pumice is one that floats and so does cellular quartz ("float-stone"). This, however, is a deception and gives no idea of the true specific gravity of the material; the buoyancy is due to the hollow spaces in the stone. In the same way a gem-stone containing cavities will not give a true value of the specific gravity.

Methylene iodide, the chemical formula of which is CH_2I_2 , has a density of 3.33, i.e. it is three and a third times as heavy as water. It is a clear, pale yellow, and perfectly mobile liquid, but is rather expensive. All stones with a specific gravity of less than 3.3 (see table on p. 26) will float, whilst all others will sink in this liquid. Hence we have a quick and ready means of distinguishing stones of similar appearance, say quartz and topaz: quartz will float and topaz sink. Methylene iodide is readily and completely miscible in all proportions with benzene (specific gravity 0.88). The various mixtures give a series of liquids ranging from 0.88 to 3.33, which can be adjusted so that any stone of specific gravity less than 3.33 will remain just suspended in the liquid, neither sinking nor floating to the surface. The specific gravity of the stone will then be the same as that of the liquid. The specific gravity of the liquid may be read at a glance by the use of indicators immersed in the liquid. Little cubes of different kinds of glass, each engraved with its specific gravity, are sold

for this purpose; or a series of known and recognizable mineral fragments may be used, such as tiny crystals of quartz, beryl, fluorite, &c.

A simple arrangement for a set of heavy liquids, which I have had in constant use for over thirty years, consists of eight corked glass tubes (about $2 \times \frac{3}{8}$ in.) placed in deep holes bored in a wooden block. The tubes are let into deep holes because methylene iodide darkens on exposure to light. It may be easily cleared again by placing a fragment of copper wire or foil in the liquid for a day or two. Each tube contains a small amount of liquid (about $\frac{3}{4}$ in. in depth). Tube No. 8 contains pure methylene iodide, and the others methylene iodide diluted with more and more benzene throughout the series, so giving a range of liquids of various densities. Each tube also contains two or three known mineral fragments to act as indicators. The minerals I have used (with others in reserve) are listed below; but this is more complete in the lower members than is needed with gem-stones, as may be seen from a comparison with the table on p. 26.

Tube No.	Mineral	Sp. gr.	Tube No.	Mineral	Sp. gr.
1	Sylvine	1.99	5	Quartz	2.65
	Rock-salt	2.15		Beryl	2.69
	Scolecite	2.27		Calcite	2.72
2	Gypsum	2.32	6	Anorthite	2.75
	Apophyllite	2.35		Dolomite	2.85
	Colemanite	2.42		Aragonite	2.94
3	Petalite	2.45	7	Phenakite	2.98
	Leucite	2.47		Tourmaline	3.02
4	Orthoclase	2.56		Fluorite	3.18
	Nepheline	2.60	8	Apatite	3.20
	Albite	2.64		Axinite	3.29
				Diopase	3.32

Benzene evaporates quickly, and if the set of tubes has not been used for some time all the indicators will be found floating on the top of the liquid. This is easily remedied by adding more benzene drop by drop from

a dropping bottle until the heaviest indicator is only just floating. The stone to be tested is dropped into, say, tube No. 5; if it sinks it is transferred with a pair of tweezers to other tubes higher up the series until it is found to float. Then add drop by drop of benzene, with a slight shaking of the tube to ensure complete mixing, until the stone remains just suspended in the liquid. Its specific gravity will lie somewhere between those of the indicators that float and sink in this tube; or one of the indicators may also remain suspended, betraying at once the stone under examination. The specific gravity of the stone between two indicators can be approximately judged from the number of the last drops of benzene added to the mixture, or from the times taken by the stone and an indicator to rise as the benzene evaporates (this can be accelerated with a blow-pipe).

Unfortunately, the use of methylene iodide is limited to those stones with a density less than 3.33. Another heavy liquid, in which all gem-stones will float, is Clerici's solution. This is an aqueous solution of thallium formate and thallium malonate, with a specific gravity of 4.0 at 10° C. and about 5.0 near 100° C. It is clear, and miscible with water in all proportions; but it is poisonous and not so convenient for use as methylene iodide.

The following table (p. 26) of the specific gravities of gem-stones is given for reference and for use in determination. The values for the various minerals have been selected as far as possible for material of gem quality. But it must be borne in mind that there may be some variation in the values. This may be in part due to the presence of impurities, cavities, or flaws in the stone. But a more important cause is that of variations in chemical composition; for example, some of the lighter magnesium or aluminium atoms may be replaced (isomorphous replacement) by heavier atoms of iron, and so cause a rise in density. Garnets

vary considerably in this way (3.6 — 4.3), and in the list they are given under their separate names. The density of opal varies with the variable amount of water it contains. The wide range in zircon has now been explained (p. 189).

Hardness is a character of importance in gem-stones, for on this depends their durability. A hard material is less affected by wear and tear than one that is softer, as may be seen, for example, in articles made of hard and soft wood. The wear of a tool depends on the hardness of the material of which it is made. It is, however, difficult to give a clear definition of hardness, as qualities of elasticity, cohesion, malleability, plasticity, toughness, brittleness, and cleavage are also involved. The apparent hardness of a body will also depend on its shape: one of irregular shape and covered with delicate protuberances will be more easily abraded than a polished sphere of the same material. It also depends on the state of aggregation: the individual particles of a friable sandstone or of chalk are harder than the main mass. There are several different ways in which degrees of hardness are measured, especially in different trades (e.g. metal and rubber), but the results are not comparable. The mineralogist defines hardness as the power of scratching. When a corner of a crystal of quartz is scored over a face of a crystal of calcite, a deep scratch and white powder are produced on the calcite. And when a corner of a crystal of calcite is scored over a face of a crystal of quartz, the calcite is again abraded, and no sign of a scratch can be seen on the quartz. Evidently quartz is harder than calcite. By trying out all kinds of minerals in this way, they can be arranged in a series according to their scratching power. Diamond heads the list and graphite is at the bottom; the latter being so soft that it soils the fingers and marks paper. This is strange, for diamond and graphite are both composed of the chemical element carbon. The

extreme difference in their degrees of hardness must here have something to do with the way in which the atoms are arranged in the two kinds of crystals. From this hardness series of minerals, F. Mohs, an Austrian mineralogist, selected in 1820 ten members with suitable gaps between to constitute a scale of hardness. This has since been universally used by mineralogists and is known as Mohs's (often misspelt Moh's) scale of hardness. But this is not an even scale, the gaps between the numbers having widely different values.

MOHS'S SCALE OF HARDNESS

No. 1. Talc.	No. 6. Felspar.
2. Gypsum.	7. Quartz.
3. Calcite.	8. Topaz.
4. Fluorite.	9. Corundum.
5. Apatite.	10. Diamond.

Gem-stones come out at the top of the list. Sets of these minerals are sold as a scale of hardness. To test the hardness of a stone, we must find the highest mineral in the scale that it will scratch, and the lowest mineral by which it can itself be scratched. If, for example, it scratches all minerals up to quartz, and it is scratched by all minerals down to topaz, then the hardness must lie between Nos. 7 and 8 on the scale. If it scratches quartz about as readily as it is itself scratched by topaz, then the hardness can be placed at $7\frac{1}{2}$; if more readily by topaz, then $7\frac{1}{4}$; or if little or no impression is made on quartz, then 7. The application of this test is, however, not quite a simple matter and requires some practice. The scratching corner and the scored surface must be carefully examined with a hand-lens to see which mineral has been crushed and powdered; and, after wiping the surface, to see whether a scratch has really been made, rather than a line of powder off the scratcher. Power of abrasion or crushing will depend partly on the sharpness of

the scratching point and on the smoothness of the surface scored upon.

When trying this hardness test, please do not disfigure and ruin a fine gem or a nice crystal by making an ugly scratch on a prominent face. Work small and use a magnifying-glass. With an unmounted gem, any tests should be made on the girdle of the stone; or when mounted, on the back, but this should be avoided if possible. A good idea of the hardness of a stone may be obtained with the use of a file or the point of a pocket-knife (hardness about $6\frac{1}{2}$), and by trying the stone on a sheet of glass (hardness about $5\frac{1}{2}$). A knife point will scratch felspar but not quartz, and will always detect a glass imitation gem. The harder a stone is, the more readily does it scratch glass: diamond has a distinct bite appreciable to the feel when applied to a glass surface. (I find my watch-glass very handy.) Talc and gypsum, Nos. 1 and 2 on the scale, are easily scratched with the finger-nail.

Hardness is a character that varies with the direction in crystals, being different on different faces and in different directions on the same face. This is very marked in the mineral kyanite, which has a hardness ranging from 5 to 7. (See also diamond, p. 118.)

As we have seen, harder minerals scratch and abrade softer ones, and if mineral specimens or gems are kept jumbled together in a box, or piled up like a rockery, some will surely suffer. This applies specially to amber and pearls, which (as shown in the following reference table, p. 26) are very much softer than mineral gemstones.

The way in which a crystal breaks when struck with a hammer and the character of the broken surfaces are matters of some importance. A harder stone that is brittle or possesses a cleavage may be broken more easily than a softer one which at the same time is tough. Cast iron is much easier to break with a hammer than wrought iron, yet it is much more difficult to work

with a file. Diamond is readily shattered, but it is extremely difficult to break a pebble of the much softer jade (nephrite or jadeite). The reason for this is that diamond possesses perfect cleavages in four directions, whilst jade consists of an interwoven mass of fibrous crystals.

SPECIFIC GRAVITIES OF GEM-STONES

Amber	1.05-1.1	Fibrolite	3.25
Jet	1.3	Diopside	3.3
Opal	2.0-2.2	Jadeite	3.3
Silica-glass	2.21	Axinite	3.3
Moldavite	2.3-2.4	Diopside	3.3
Sodalite	2.3	Kornerupine	3.3
Lazurite	2.4	Idocrase	3.3-3.4
Orthoclase	2.56	Olivine	3.3-3.5
Chalcedony	2.6	Epidote	3.3-3.5
Cordierite	2.6	Sphene	3.4
Quartz	2.65	Hypersthene	3.4
Scapolite	2.6-2.7	Rhodonite	3.4-3.6
Coral	2.6-2.7	Diamond	3.52
Oligoclase	2.66	Topaz	3.5-3.6
Turquoise	2.6-2.8	Grossular	3.5-3.6
Beryl	2.6-2.9	Uvarovite	3.5-3.7
Labradorite	2.7	Kyanite	3.6
Pearl	2.7-2.8	Spinel	3.6-3.7
Lapis-lazuli	2.7-2.9	Benitoite	3.65
Beryllonite	2.85	Chrysoberyl	3.7
Pollucite	2.9	Staurolite	3.7
Danburite	3.0	Pyrope	3.7-3.8
Phenakite	3.0	Andradite	3.8-3.9
Nephrite	3.0	Corundum	4.0
Tourmaline	3.0-3.2	Zircon (amorphous)	4.0
Eucrase	3.1	Willemite	4.1
Fluorite	3.18	Spessartine	4.1-4.3
Andalusite	3.1-3.2	Rutile	4.2-4.3
Spodumene	3.1-3.2	Zircon (normal)	4.7
Apatite	3.2	Hematite	5.2
Enstatite	3.2	Cassiterite	6.9

HARDNESS OF GEM-STONES

Amber	..	..	2-2½	Epidote	..	..	6½
Jet	..	..	3½	Scapolite	..	..	6½
Pearl	..	..	3½	Pollucite	..	..	6½
Coral	..	..	3½	Benitoite	..	..	6½
Fluorite	..	..	4	Axinite	..	..	6½
Apatite	..	..	5	Andradite	..	..	6½
Diopase	..	..	5	Jadeite	..	..	6½
Kyanite	..	..	5-7	Spodumene	..	..	6½
Sphene	..	..	5½	Quartz	..	..	7
Lazurite	..	..	5½	Danburite	..	..	7
Sodalite	..	..	5½	Grossular	..	..	7
Enstatite	..	..	5½	Spessartine	..	..	7
Hypersthene	..	..	5½	Tourmaline	..	..	7-7½
Beryllonite	..	..	5½	Cordierite	..	..	7½
Willemite	..	..	5½	Pyrope	..	..	7½-7½
Moldavite	..	..	5½	Almandine	..	..	7½
Opal	..	..	5½-6½	Andalusite	..	..	7½
Silica-glass	..	..	6	Staurolite	..	..	7½
Felspars	..	..	6	Fibrolite	..	..	7½
Rhodonite	..	..	6	Euclase	..	..	7½
Turquoise	..	..	6	Zircon	..	..	7½
Hæmatite	..	..	6	Beryl	..	..	7½
Chalcedony	..	..	6½	Phenakite	..	..	7½
Cassiterite	..	..	6½	Topaz	..	..	8
Rutile	..	..	6½	Spinel	..	..	8
Diopside	..	..	6½	Chrysoberyl	..	..	8½
Nephrite	..	..	6½	Corundum	..	..	9
Olivine	..	..	6½	[Carborundum	..	..	9½]
Idocrase	..	..	6½	Diamond	..	..	10

CHAPTER IV

Forms of Crystals

AN important feature of gem-stones is that—with the single exception of opal (also amber and jet)—they consist of crystallized matter; and in the majority of cases each gem consists of a single individual crystal. The more perfect and regular the crystallization, the more perfect is the resulting gem. Although the external form of the crystals is of course not evident in cut stones, yet some knowledge of crystallography is essential for the proper understanding of their optical characters.

The atoms which build up the vast array of chemical substances, elements as well as compounds, are grouped together in certain ways with definite patterns, and there is a continuous repetition of this pattern throughout space of three dimensions. Each substance, and gem-stone, has its own characteristic pattern.

We can imagine the atoms situated at the knots of a network or the nodes of a lattice (figs. 2 and 3). As a result of this it will be seen that there are certain lines and planes of atoms continuous throughout the structure. In fig. 2, showing a square network in two dimensions, in addition to the horizontal and vertical lines of atoms, several other lines can be traced. The dotted lines *a*, diagonally across the square, pass through every knot. The lines *b* pass through every second knot downwards, and the lines *c* through every third knot. Others could be drawn through every fourth and other knots. Similarly, the dotted lines *b'* and *c'* pass through every second and third knot in the horizontal lines.

In fig. 3 four of the square networks, as in fig. 2, are piled one above another in the third dimension, giving a cubic lattice. This becomes much more complex. In addition to the original four networks, there are now eight others of a similar character—four in the plane of the paper, and four extending from front to back. Each of the sets of planes is parallel to the faces of a cube. But these are not the only planes of atoms that can be traced in such a structure. The vertical

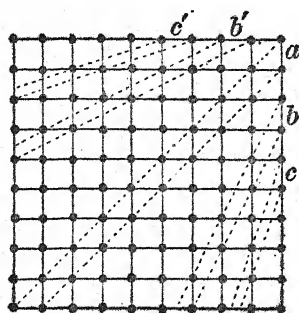


Fig. 2.—Square network in two dimensions

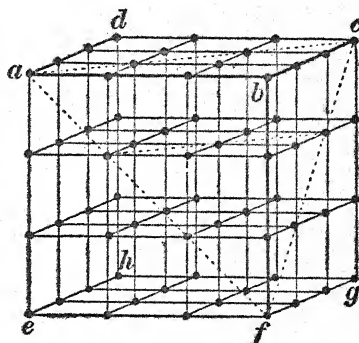


Fig. 3.—Simple cubic lattice in three dimensions

plane $acge$ shows sixteen dots in the picture, and parallel to this there is rank upon rank of similar planes, if we imagine the structure to be extended indefinitely with millions of dots. The next plane parallel to and in front of $acge$ contains twelve dots in the picture. But the whole structure now has a symmetrical repetition, and there are five other plane directions similar to $acge$, namely, $bdhf$, $afgd$, $behc$, $bgha$, and $cfed$. The inclined plane through the three points acf contains ten points in the picture (nine along the edges and one in the centre). Such a set of parallel planes is symmetrically repeated through the points ach , dbe , and dbg , there being four such directions parallel to the faces of a regular octahedron. But this is not all. An ingenious

reader will be able to trace hundreds of other planes of atoms. (Better than any crossword puzzle!)

The structure outlined in the preceding paragraph is the simple cubic lattice. There are two other kinds of cubic lattice: face-centred with a dot in the centre of each face of a cubic cell; and body-centred with a dot in the centre of each cubic cell. If we take unequal lengths between the points along the three main directions, and also vary the angles (not all right angles) between these directions, then we get other types of lattices of which there are fourteen in all. But this is only the beginning of the problem. The dots can be arranged with symmetrical repetitions to fill space in 230 different ways—known as the 230 space-groups. Think of all the different patterns of wall-paper that you have seen in two dimensions, and then imagine what would happen if the whole space of the room were filled with them. These matters may safely be left to the specialist in crystal structure, and they need not alarm the admirer and student of gem-stones.

That such complications do not exist only in the minds of philosophers, but also in crystals (and gem-stones), has been proved within the last twenty years by means of X-rays. The planes of atoms which we have traced out have the power of reflecting X-rays, and by measuring the angles of reflection the distances between the planes and between the atoms themselves can be calculated. These distances are of course excessively minute. In fig. 3, if the atoms along directions parallel to the cube edges are alternately sodium and chlorine, then the figure represents the structure of rock-salt. The distance between adjacent sodium and chlorine atoms has been carefully measured as 2.814 Ångström units, or 2.814×10^{-8} cm. (0.000,000,028,14 cm.), or rather more than a hundred-millionth of an inch. If we took a crystal of rock-salt measuring one inch along the edge (1 cubic inch) and reproduced the whole structure on the same scale as in fig. 3, the

drawing would be nearly a thousand miles across.

The internal structure of crystals suggested above finds an expression in their external form. A single crystal growing freely (not in a confined space, or crowded amongst other crystals) shows a development of plane surfaces which are usually quite smooth and brilliant. These planes or crystal-faces are parallel to the planes of atoms that we have been considering, and are thus important directions in the crystal.

From the point of view of a student of gem-stones this external form of crystals is of much interest and importance. Each mineral species, i.e. each essentially different kind of gem-stone, has a crystalline form characteristic of itself, and if crystal-faces are present we can tell at a glance to which mineral the crystal belongs. Even when the crystal is water-worn, as is often the case with gem-stones, there is often some indication of the original shape. A knowledge of the external forms of crystals is therefore of considerable importance, and enables us to distinguish at once between, say, a red garnet and a ruby, or between a green tourmaline and an emerald.

Fig. 4 is a drawing of a regular octahedron, a solid bounded by eight equilateral triangles in four parallel pairs. Crystals of diamond and spinel are of this form. Fig. 5 shows the eight faces of the octahedron unfolded on to a flat surface. (A spherical surface cannot be so unfolded, hence the difficulty with maps of the globe.) A reader sufficiently interested in the matter should draw this diagram, preferably on a larger scale, on a piece of stiff paper, cut out along the full lines, and fold along the dotted lines. The result will be a model of an octahedron, if all the angles have been made exactly 60° . With the aid of such a model the several curious properties of the octahedron will be seen much more clearly than from the drawing in fig. 4. It will be seen that the model can be cut into two similar and equal halves along the planes $ABA'B'$, $ACA'C'$, and $CBC'B'$

and if one half be placed against a mirror the other half will be reproduced, giving the appearance of the full model. These planes are called *planes of symmetry*, here the three cubic planes of symmetry. The octahedron also has six other planes of symmetry (dodecahedral planes), each of which passes through two corners and the middles of two opposite edges, e.g. a plane through CC' and the middles of the edges AB and

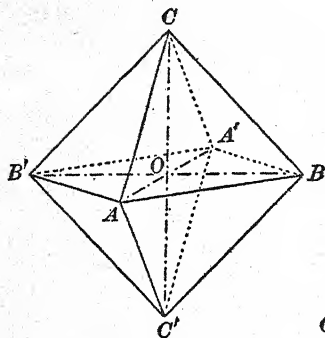


Fig. 4.—Octahedron, a regular eight-faced solid

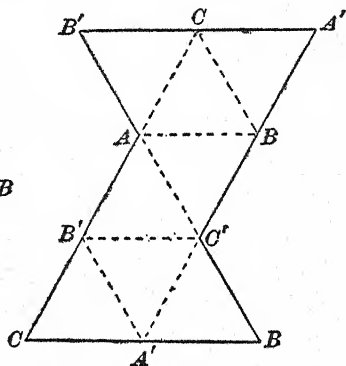


Fig. 5.—Net for the construction of a model of the octahedron

$A'B'$, or through BB' and the middles of AC and $A'C'$.

In addition to these nine ($3 + 6$) planes of symmetry, the octahedron also has thirteen ($3 + 4 + 6$) *axes of symmetry* of three kinds. In fig. 4 the three dash-and-dot lines joining opposite corners and intersecting at the centre of the crystal are axes of tetrad symmetry. If the model be rotated about any one of these axes through an angle of 90° , it comes into the same position as before—a covering position. This operation is repeated four times during a complete rotation of 360° about each axis, hence the term tetrad axis. Perpendicular to each of the four pairs of parallel faces of the octahedron, and again passing through the centre of the crystal, is a triad axis, about which rotation of

120° gives a covering position, repeated three times during a complete rotation of 360° . There are four of these triad axes. Next we have six dyad axes with rotations of 180° and only two covering positions for a complete rotation. These dyad axes pass through the centre of the crystal to the middles of opposite edges. Finally, the crystal possesses a *centre of symmetry*. Every point on the surface of the crystal has a corre-

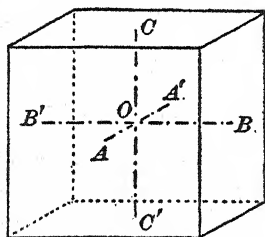


Fig. 6.—Cube or hexahedron, a regular six-faced solid

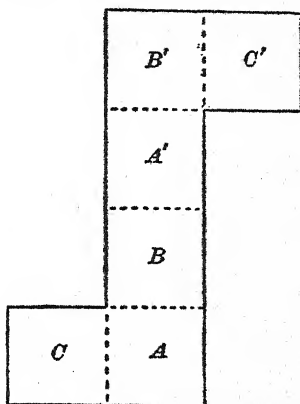


Fig. 7.—The surface of the cube unfolded

sponding point on the opposite side and at an equal distance from the centre. We thus see that the octahedron is a highly symmetrical body.

The cube or hexahedron (fig. 6), a regular solid bounded by six equal squares, has the same high degree of symmetry as the octahedron; namely, three cubic planes of symmetry, six dodecahedral planes, three tetrad axes of symmetry, four triad axes, six dyad axes, and a centre of symmetry. Crystals of diamond, especially those from the Belgian Congo, sometimes have the form of the cube. Although the figures of the octahedron and the cube differ so very much in appearance, yet there is a very close crystallographic

relation between the two. If we chop off the corners of the cube, we obtain an octahedron; and if we chop off the corners of the octahedron, we get a cube. In the first case the resulting figure is obtained by joining the points at the centre of each face ($ABC A'B'C'$ in fig. 6); and in the second by joining the points at the centre of each octahedron face.

Figs. 8, 9, and 10 show the stages in passing from the octahedron to the cube and vice versa. They represent crystals consisting of a combination of two simple

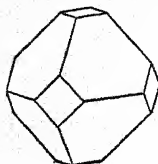


Fig. 8

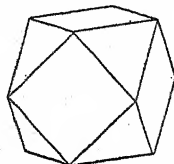


Fig. 9

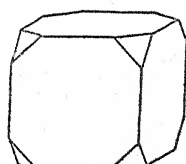


Fig. 10

Combinations of the cube and octahedron

In fig. 8 the octahedron predominating; fig. 9 the cubo-octahedron; in fig. 10 the cube predominating

forms—here the cube and the octahedron. This *combination of forms* is very common in crystals, in fact, a usual feature. Fig. 9, bounded by six squares and eight equilateral triangles, is the cubo-octahedron, which is one of the Archimedean solids of geometry.

Here we may remark that the regular solids of geometry are not necessarily possible forms of crystals. All of them do not conform with the laws of crystal symmetry. The octahedron and cube, and also the tetrahedron, of the five Platonic solids are possible crystal forms, but not the dodecahedron (closed by 12 pentagons) and the icosahedron (20 equilateral triangles). The tetrahedron is bounded by four equilateral triangles. Fig. 11 shows its relation to the cube. It is also related to the octahedron by extending four alternate faces of this and suppressing the four parallel faces. This form has only part of the full symmetry of

the cube and octahedron; namely, six dodecahedral planes of symmetry, four triad axes, and three dyad axes (in place of the three tetrad axes), but no cubic planes of symmetry and no centre of symmetry. The tetrahedron is a rare form in crystals of diamond.

The three simple forms of crystals we have so far considered belong to the cubic system of crystals. But there are several others, the more important of which are the rhombic-dodecahedron and the icositetrahedron (figs. 51 *a* and *d* in the garnet chapter), which are the

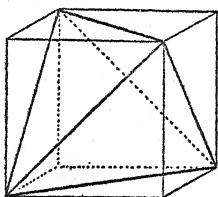


Fig. 11.—Regular tetrahedron inscribed in a cube

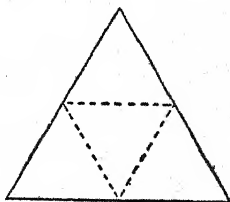


Fig. 12.—The surface of the tetrahedron unfolded

usual forms of garnet crystals. With combinations of the several simple forms, some cubic crystals may be bounded by hundreds of facets, but they are all arranged on the crystal according to the laws of symmetry. Further, they can all be referred to three equal *crystallographic axes* at right angles. In figs. 4 and 6 these axes are drawn with a dash and dot.

So much for the *cubic system* of crystals, of which diamond, spinel, and the garnets are important representatives amongst gem-stones. In discussing the internal structure of crystals, it was mentioned on p. 30 that different types of lattices could be derived by varying the distances along the main directions and also the angles between these directions. Now these directions are the crystallographic axes to which the external faces of crystals are referred. If we take in fig. 4 the axes *AA'* and *BB'* of equal length, but make

the third axis CC' either longer or shorter, we then have a different state of affairs, and by joining up the ends of the axes, we still have an eight-faced figure, but not a regular octahedron. If the axis CC' is taken longer, we have a steep square pyramid, and if shorter, a flat square pyramid. These are crystals of the *tetragonal system*, of which there are again special degrees of symmetry and a variety of simple forms as well as combinations of forms. Zircon is an important example of this system of crystals (figs. 53 $a-d$, p. 188).

Another obvious variation is to take the three axes AA' , BB' , and CC' all of unequal lengths, but still at right angles. This gives the *orthorhombic system* (or rhombic system), of which topaz, olivine, and chrysoberyl are examples. Next we can vary the angles between the axes, and so derive two more systems, the *monoclinic* (with one angle not a right angle) and the *triclinic* (with no right angles between the axes); in both of these systems the axes are all of unequal lengths. Still another variation is possible by making all the angles between the three axes equal but not right angles and all the axes of equal length. This gives the *rhombohedral system*, which may be regarded as a sub-system of the *hexagonal system*. These are of rather a special type, but they are of importance as being the forms in which ruby and emerald crystallize. Fortunately no other variations are possible according to the strict laws of crystallography.

Suppose we take a cube by two opposite corners and stretch it out in the direction of a cube diagonal, we shall then get a solid like fig. 13, which is called a rhombohedron, because it is bounded by rhomb-shaped faces. The six faces are all of equal size and the twelve edges all of equal length. Further, the axes of reference are all of equal length, and the angles between them are all equal but not right angles. A cube compressed, instead of stretched, along a cube diagonal will give an obtuse rhombohedron (fig. 14). These rhombohedra

possess a unique triad axis of symmetry, which is always placed vertically in drawings of such crystals. For this reason the drawings in figs. 6, 13 and 14 differ in orientation. Suppose now we continue to stretch the acute rhombohedron, the three upper and the three lower faces will approach nearer and nearer to the vertical axis, and at infinity they will be parallel to it. We now have the six faces of a hexagonal prism. Similarly, by compressing the obtuse rhombohedron

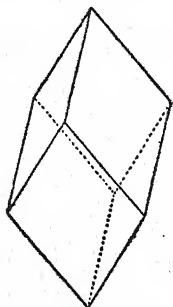


Fig. 13.—Acute rhombohedron

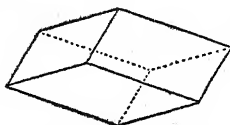


Fig. 14.—Obtuse rhombohedron

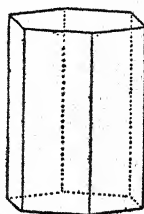


Fig. 15.—Combination of hexagonal prism and basal pinakoid

the limit will be a pair of planes perpendicular to the vertical axis. Fig. 15 is a combination of these two forms, the hexagonal prism and basal pinakoid. Neither of these forms can by itself enclose space, and they can be present on crystals only as combinations of forms. Fig 15, which represents a crystal of emerald, has a unique sixfold or hexad axis. A rotation of 60° about this axis brings the crystal into the same relative position as before, and six such operations make a complete rotation of 360° .

This gives us seven systems of crystals, each endowed with different degrees of symmetry. But it must be mentioned that in each system there are several classes in which the symmetry is only partial, allowing in certain forms the development of only half or a quarter

of the full number of faces. These are called hemihedral (half-faced) or tetartohedral forms, in distinction to the holohedral (full-faced) forms. There are altogether thirty-two of these crystal-classes, only a few of which include any gem-stones. Particulars of these will be found in textbooks on crystallography and mineralogy, and all the essentials are concisely stated with many figures of crystals in my article "Crystallography" in the *Encyclopædia Britannica* (11th edition, 1910). The main features are tabulated at the end of this chapter (p. 41), together with a list of the gem-stones that crystallize in each system. The full degree of symmetry is stated for each of the holohedral classes, together with the partial symmetry of the few hemihedral classes in which gem-stones are represented. This table is intended for reference, not for reading.

The angles of cubic crystals are fixed by geometry, and are the same for all substances (diamond, spinel, gold, iron, alum, &c.) that crystallize in this system. Those between cube faces are 90° , between adjacent octahedron faces $109^\circ 28'$, and between adjacent cube and octahedron faces $125^\circ 16'$. Usually, however, the supplements of these angles are stated, viz. 90° , $70^\circ 32'$, and $54^\circ 44'$, these being the angles actually measured on the reflecting goniometer (angle measurer) and used in calculations. In all of the other systems each substance has a set of interfacial angles peculiar to itself, and by measuring these angles we can identify the substance. The angles are dependent on the relative lengths of, and the angles between, the crystallographic axes of reference. From the angles we can calculate the lengths of the axes, and vice versa, knowing the lengths of the axes, we can calculate the angles. For example, in topaz the lengths of the axes OA , OB , OC (compare fig. 4) are stated as the axial ratios $a:b:c = 0.5285:1:0.4770$, corresponding to an angle of $55^\circ 43'$ between the pair of prism faces m , and of $87^\circ 18'$ between the pair of dome faces f (fig. 50b, p. 174).

The different faces on crystals are distinguished by indices, which are given by the relative lengths the faces intercept on the axes of reference. In fig. 2, for example, the indices of the lines a , b , c could be written (1,1), (1,2), (1,3), corresponding with the relative distances they meet the sides of the square. Similarly, with three co-ordinate axes, a plane meeting the axes at unit length at A , B , C (fig. 4) has the indices (111). This is the simple symbol of the octahedron. A plane cutting the OA axis at A , the OB axis at half its length, and the OC axis at one-third has the indices (123). Cube faces cut only one axis and are parallel to the other two, and the indices of the three faces A , B , C (fig. 6) are (100), (010), and (001) respectively.

Irregularities in the development of crystals are frequent. Few actual crystals show the model-like shapes represented in the accompanying figures. During the growth of a crystal from solution, it usually happens that more material is supplied on one side than on another, with the result that the crystal grows lopsided. A crystallographic cube, for example, may have the shape of a square or rectangular slab or column. With combinations of forms, certain faces are often missing. But the internal structure and the angles between the faces always remain the same, and such faces that are developed are placed in their true symmetrical position and the parallelism of their edges is preserved (see figs. 49 $a-c$, p. 170). The arrangement of the faces in zones, or bands, around the crystal with sets of parallel edges will be noticed in these figures.

Cleavage is an important character of crystals, and one intimately connected with their internal structure. If we have a parallel set of densely packed planes of atoms with a wide distance between the planes, it is likely that this will be a direction of weakness in the structure along which it will break. The crystals of different substances have different degrees of cleavage, and this character affords an important means of dis-

tinguishing different minerals. There can, for instance, be no mistake in recognizing mica, a crystal of which can be readily torn up into thin paper-like sheets, each with a smooth and brilliant surface. Euclase (named from *eu* well, and *κλάσις* breaking) and fibrolite also have a wonderful cleavage. If care be not taken in cutting these gems the crystals will collapse like a pile of cards, or if dropped they will split. Diamond also has a good cleavage, here in four directions parallel to the faces of the octahedron. Advantage is taken of this property in the process of diamond cutting; a large crystal may be divided or smaller irregularities removed. A knife edge is placed in the correct position parallel to an octahedron plane and the back of the knife struck a smart blow; the crystal then falls in two along smooth and shining surfaces. It is an instructive experiment to produce the cleavage in rock-salt, calcite, or baryte with a knife and small tapping hammer. To do this requires some knowledge of crystallography, which may or may not have been gained from this chapter. Another gem mineral possessing a perfect cleavage is topaz, here in one direction parallel to the basal plane. This affords an easy means of distinguishing between topaz and quartz when a broken surface, even on a pebble, can be inspected. Spodumene (kunzite) has two perfect cleavages parallel to the prism planes. Feathered flaws in gem-stones are due to cleavage, and a cleavage crack seen through the stone often shows coloured bands (Newton's rings).

In other crystals which do not possess a facility of breaking in a certain direction, the character of the fractured surfaces, or "fracture", sometimes affords a distinguishing feature. It may be conchoidal (with concentric ringed markings as on the surface of a bivalve shell) or uneven.

THE CRYSTAL SYSTEMS OF GEM-STONES

CUBIC SYSTEM.—Three crystallographic axes all of equal length and all at right angles.

3 + 6 symmetry planes, 3 tetrad axes, 4 triad axes, 6 dyad axes, centre of symmetry.

Diamond, spinel, garnet group, lazurite, sodalite, pollucite, fluorite.

TETRAGONAL SYSTEM.—Two of the crystallographic axes of equal length and the third either longer or shorter; all at right angles.

2 + 2 + 1 symmetry planes, 1 tetrad axis, 2 + 2 dyad axes, centre of symmetry.

Zircon, idocrase, cassiterite, rutile.

ORTHORHOMBIC SYSTEM.—Three crystallographic axes of unequal lengths and all at right angles.

1 + 1 + 1 symmetry planes, 1 + 1 + 1 dyad axes, centre of symmetry.

Topaz, olivine, chrysoberyl, andalusite, enstatite, bronzite, hypersthene, cordierite, fibrolite, staurolite, danburite, beryllonite.

MONOCLINIC SYSTEM.—Three crystallographic axes of unequal lengths; two axes inclined at an oblique angle but both at right angles to the third axis.

1 symmetry plane, 1 dyad axis, centre of symmetry.

Spodumene, nephrite, jadeite, diopside, epidote, euclase, sphene, orthoclase.

TRICLINIC SYSTEM.—Three crystallographic axes of unequal lengths; none at right angles.

Centre of symmetry only.

Axinite, kyanite, rhodonite, oligoclase, labradorite, turquoise.

HEXAGONAL SYSTEM.—Three equal crystallographic axes inclined at 60° and all in one plane, and a fourth axis of different length perpendicular to this plane and coincident with the hexad axis of symmetry.

3 + 3 + 1 symmetry planes, 1 hexad axis, 3 + 3 dyad axes, centre of symmetry.

Beryl (emerald and aquamarine).

Bipyramidal Class.—1 symmetry plane, 1 hexad axis, centre of symmetry.

Apatite.

RHOMBOHEDRAL SYSTEM.—Three equal crystallographic axes mutually inclined at the same angles, which are not right angles. (The four axes as in the hexagonal system are often alternatively employed.)

3 symmetry planes, 1 triad axis, 3 dyad axes, centre of symmetry.

Corundum (ruby and sapphire), hæmatite.

Ditrigonal Pyramidal Class.—3 symmetry planes, 1 triad axis, no centre.

Tourmaline.

Trapezohedral Class.—1 triad axis, 3 dyad axes, no centre. Quartz (rock-crystal, amethyst, citrine).

Rhombohedral Class.—1 triad axis, centre of symmetry.

Phenakite, willemite, diopase.

Ditrigonal Bipyramidal Class.—3 + 1 symmetry planes, 1 triad axis, 3 dyad axes, no centre.

Benitoite.

NON-CRYSTALLINE (AMORPHOUS).—Opal, amber, jet, moldavite, silica-glass.

CHAPTER V

Optical Characters of Precious Stones: their Action on Light

LIGHT, of all colours and all wave-lengths, travels with a velocity of about 186,000 miles per second, slightly less in air than in a vacuum. But when it enters a denser medium, such as glass or a crystal, the velocity receives a check proportional to the index of refraction of the medium. In diamond the velocity of red light is about 77,000 miles per second, and of violet light only about 75,000 miles per second. [I am not interested in motor-car racing.] It takes longer for a violet ray to get round inside a brilliant-cut diamond before flashing out from the front of the gem than it does for a red ray travelling along the same path. As a result of this check in the velocity, the path of the ray is deflected when it enters the stone. This is known as the refraction of light, and the amount of the refraction or bending gives a measure of the index of refraction. The refractive index is a character of importance in gem-stones, showing considerable differences in different kinds of stones. It is therefore a useful aid in their identification.

In figs. 16 and 17 a ray of light AO striking the surface of water or diamond at O is partly reflected from the surface (otherwise we would not see the object), and part enters the denser medium travelling along a deflected path OB . The amount of bending is given by the ratio of the sine of the angle of incidence to the sine of the angle of refraction (these angles i and r

being measured to the normal CD to the surface), or by $\sin i / \sin r = AC / BD$, which is a measure of the index of refraction. Water has a refractive index of 1.333, so in fig. 16 the length AC is 1.333 times as long as BD . Diamond with a higher refractive index of 2.42 causes a more violent bending of the ray; in fig. 17 OA is 2.42 times as long as BD . An object at B when viewed from A will appear much more displaced when seen through diamond than through water.

Since the ray on entering the denser medium is deflected towards the normal CD , it is clear that there

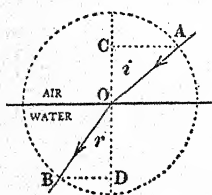


Fig. 16.—Refraction of light in water

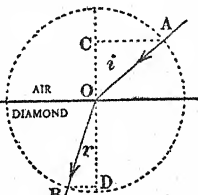


Fig. 17.—Refraction of light in diamond

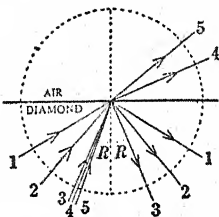


Fig. 18.—Refraction and internal total reflection in diamond

can be no difficulty for any ray to enter into water or diamond from air. But rays travelling in the opposite direction may meet with a difficulty. With an increase in the angle r (now the angle of incidence) there is a more rapid increase in the angle i , and when this reaches 90° the ray of light can only skim along the surface. With any further increase the ray cannot emerge at all, but is reflected back into the denser medium, and now at a different angle, the angle of reflection (not refraction) being equal to the angle of incidence (fig. 18). This is called the "critical angle of total reflection" (R), and $\sin R = 1/n$, where n is the index of refraction. For diamond this critical angle is about $24\frac{1}{2}^\circ$, and for water $48\frac{3}{4}^\circ$. Light cannot get out of diamond so easily as out of water. Each gem-stone has its own characteristic critical angle. Total reflection from the surface of water

is very simply demonstrated by placing a pencil in a glass of water and viewing it from below. If an aquarium is viewed from below at an angle greater than the critical angle, the fishes will be seen upside down.

This critical angle is a matter of considerable importance in the cutting of gem-stones. Light entering the front of a gem must not be allowed to pass out at the back, but must be reflected at the back facets to flash out from the front and so enhance the brilliancy of the gem (fig. 19). This will govern the angles at which the facets are set, and in a properly cut and proportioned gem these angles will vary with the kind of stone.

So far, we have considered light of a single wave-length or colour, i.e. monochromatic light. But the refractive index of a substance varies with the different wave-lengths, increasing in amount for shorter and shorter waves. The refractive index for violet light is always greater than for red light. The difference between these two indices is a measure of the *dispersion*; and this again is a quantity that differs in different gem-stones, and is very high in diamond. On this depends the breaking up of white light into its component colours, as shown in the spectrum. The ray *OB* (figs. 16 and 17) is not a single ray, but a sheaf of rays of all colours. In passing out from a parallel-sided plate these will be intermingled; but if the surface of emergence be at an angle with the first surface, so forming a prism, then there is a further separation of the colours to give a spectrum. This is illustrated in

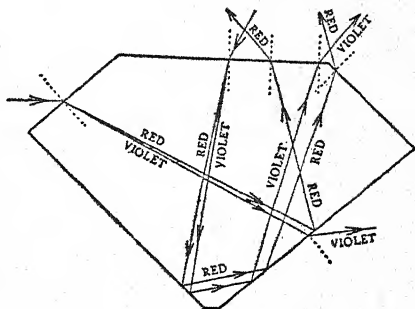


Fig. 19.—Splitting up of light in a brilliant-cut diamond: refraction and internal total reflection

fig. 19, but with the dispersion grossly exaggerated and with internal total reflections. With the facets set at different angles, a brilliant-cut diamond acts as a prism and gives flashes of prismatic colours which are refracted out from the several facets. The ray shown entering at the top of the gem is twice reflected inside at angles greater than the critical angle and can finally emerge at angles less than the critical angle. Fig. 19 also illustrates how total reflection near the critical angle can help in splitting up the light into its component colours. The violet refracted part of the ray entering the stone from the left meets the opposite facet at less than the critical angle ($23^{\circ} 56'$ for violet in diamond), and it can therefore pass out; whilst the red portion meets the same facet at just over the critical angle ($24^{\circ} 36'$ for red), and it is totally reflected at this surface.

The patient reader (if he has got so far) must now be prepared for a further complication. What has been said up to now applies only to cubic crystals, which are described as being optically isotropic or singly refracting. In them, as in glasses and liquids, light travels with the same velocity in every direction, and the optical properties show no variation with direction within the crystal. All other crystals are doubly refracting (or birefringent) and light travels through them with different velocities in every direction, and the optical properties are different in different directions (with certain exceptions). Further, a ray of light entering such a crystal is not only split up into its several colours, but the rays of each colour are themselves each split up into two oppositely polarized rays. In ordinary light, and the light we have dealt with in cubic crystals, the wave vibrations are in all directions perpendicular to the path of the ray (like a plummet which may swing in any direction). In polarized light the wave vibrations are confined to one plane, the ray itself, of course, also lying in this plane

(as with a pendulum). The two polarized beams in these crystals are polarized in planes at right angles, one, say, vibrating up and down and the other from left to right. In the mineral calcite these two beams are widely separated, and through a clear block of Iceland-spar, objects are seen double, hence it is called doubly-refracting spar. In a large cut gem-stone (especially zircon) the edges of the back facets can sometimes be seen double for the same reason.

The study of polarized light in crystals is full of interest and complications, and for details reference must be made to textbooks on crystal optics or to chapters on the subject which are usually included in the textbooks on crystallography and mineralogy. All crystals can be grouped optically into three main classes:

1. Optically isotropic, including crystals of the cubic system; e.g. diamond, spinel, garnets.
2. Optically uniaxial, including crystals of the tetragonal, rhombohedral, and hexagonal systems; e.g. zircon, corundum, quartz, beryl, &c.
3. Optically biaxial, including crystals of the orthorhombic, monoclinic, and triclinic systems; e.g. topaz, olivine, sphene, axinite, &c. (For complete list see the reference table on pp. 64-65.)

Cubic crystals and glasses have no action on plane polarized light. (But here again we are up against a further complication and exception to a general rule. Some cubic crystals of low degree of symmetry are circularly polarizing or "optically active", being capable of rotating the plane of polarization; but fortunately none of these is known among gem-stones.) This general rule affords a simple means of distinguishing cubic crystals, and also of distinguishing a coloured glass imitation from a genuine (not cubic) stone. For this purpose a polariscope or polarizing microscope is needed. This differs from an ordinary microscope in being fitted with a rotating stage and two nicol prisms,

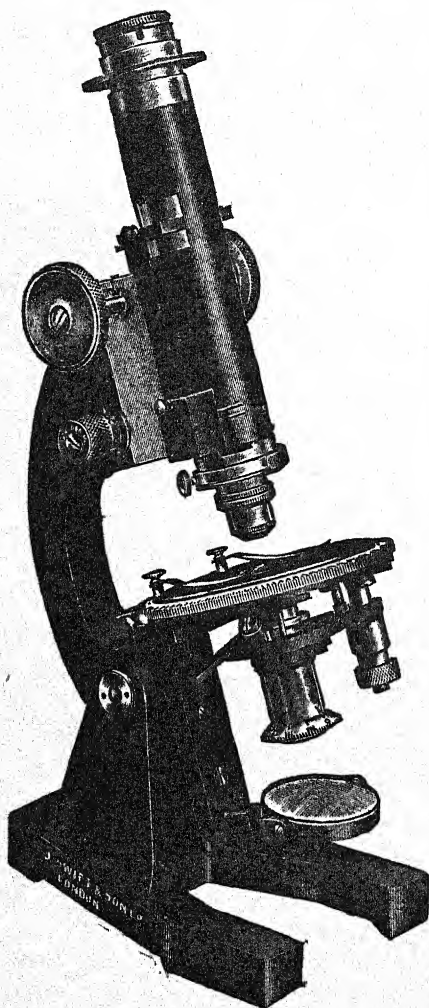


Fig. 20.—Polarizing (or petrographical) microscope

a polarizer and an analyser. A clear view can be obtained through each of these separately, but when they are "crossed", they cut out all the light. A cubic crystal or glass, when placed on the stage of the microscope between "crossed nicols", remains dark throughout a complete rotation of the stage. But here another warning. Some cubic crystals show anomalous double refraction due to strain, and this can only be judged by experience.

In cubic crystals the travelling of the rays is very much as you please, though they must keep on in straight lines. But in the more complex doubly-refracting crystals

there are strict traffic regulations, as well as a variety of speed limits. In uniaxial crystals two classes of

travellers are allowed. One of these, the ordinary ray, must respect the laws of refraction as in cubic crystals, but it is constrained to vibrate only perpendicular to one line in the crystal. If it happens to be travelling along this line (or rather direction), then the vibrations can be in a variety of directions perpendicular to this line, and these can waggle sideways or up and down just as they please, as in a cubic crystal. In this one direction, uniaxial crystals behave like cubic crystals and are optically isotropic. They remain dark between crossed nicols. This unique direction is called the "optic axis" of the crystal. It coincides with the fourfold, threefold, or sixfold symmetry axes in tetragonal, rhombohedral, or hexagonal crystals. For an ordinary ray travelling in any other direction inside the crystal the vibrations can be perpendicular to only one plane, for there is only one plane that will contain both the path of the ray and the optic axis. The ray is then plane polarized. All the ordinary rays, whatever their direction, have the same velocity for light of one colour and in the same kind of crystal. Corresponding to this we have the ordinary index of refraction for a uniaxial crystal, which is usually denoted by ω . This, of course, varies slightly with the wave-length or colour of the light, and it has different characteristic values in different minerals.

The other class of ray in uniaxial crystals is the "extraordinary ray", so called because it does not obey the ordinary law of refraction, as does the ordinary ray. It can vibrate only in the single direction parallel to the optic axis. Since vibration-directions are perpendicular to the path of the ray, it follows that an extraordinary ray cannot travel along the optic axis. It has its full strength, as it were, when travelling in any direction perpendicular to this axis. In such a direction the velocity of the ray and the corresponding index of refraction (here the extraordinary index, denoted ϵ , epsilon) have maximum and

characteristic values. For any intermediate direction of the ray between these two extremes (polar and equatorial in the crystal), the values for refractive index lie between ω and ϵ . Now ϵ may be either greater or less than ω , according as the velocity of the extraordinary ray is less (slower) or greater (faster) than that of the ordinary ray. If ϵ is greater than ω , we have an "optically positive" crystal, and if ω is greater than ϵ , then an "optically negative" crystal. This may seem a trivial academic point, but it is a help in distinguishing different kinds of uniaxial crystals. For example, corundum, beryl, tourmaline, scapolite, and apatite are optically negative; while quartz, phenakite, diopase, zircon, and benitoite are optically positive.

The optics of biaxial crystals are still more involved. Here there is no ordinary ray, but three extraordinary rays, each with its own vibration-direction. These three vibration-directions or axes of optical elasticity are all at right angles to one another, and they are related in certain definite ways to the crystallographic axes and symmetry axes of the crystal; and from their orientation it is possible by optical means to distinguish between orthorhombic, monoclinic, and triclinic crystals. In biaxial crystals there are two unique directions in which all the rays have the same velocity and refractive index, and along which the properties are much the same as along the optic axis of a uniaxial crystal. The angle between this pair of optic axes is called the "optic axial angle", and it has a characteristic value for different minerals. Corresponding to the three extraordinary rays in these crystals there are three principal indices of refraction, referred to as alpha, beta, and gamma, α , β , γ , of which α is the smallest and γ the largest. But unless the rays are travelling in a direction perpendicular to their own particular vibration-directions, only intermediate values are measured of the refractive indices. Optically positive and negative

are here also distinguished as in uniaxial crystals. When the vibration-direction of the greatest index γ is the "acute bisectrix", i.e. bisects the acute angle between the optic axes, then the crystal is said to be positive; when α is the acute bisectrix the crystal is negative. This difference is also shown in the relative magnitudes of the three refractive indices. When β is nearer to α than it is to γ , then the crystal is positive; and if β is nearer to γ than to α , then negative. For example, in topaz the three principal indices of refraction have for yellow sodium-light the numerical values α 1.619, β 1.620, γ 1.627, and the crystal is positive; in andalusite the indices are α 1.634, β 1.639, γ 1.643, and the crystal is negative.

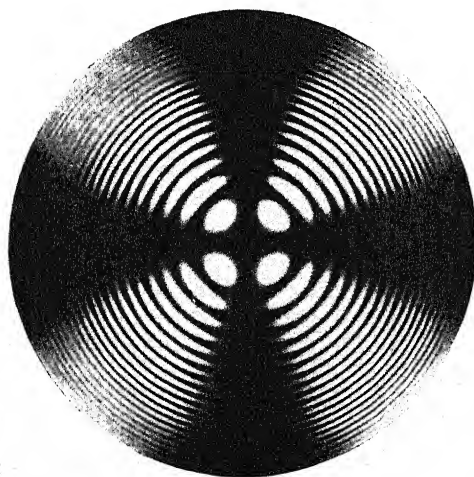
This leads us to another important optical character, which is of great determinative value in crystals, that of the double refraction or birefringence. A measure of the strength of this is given by the difference between the greatest and least indices of refraction. From the figures given above this is $\gamma - \alpha = 0.008$ for topaz and 0.009 for andalusite. Similarly, in uniaxial crystals the strength of the birefringence is given by $\epsilon - \omega$ or $\omega - \epsilon$ according as to whether we are dealing with a positive or a negative crystal. In corundum the indices have for yellow light the values ϵ 1.760, ω 1.768, and the difference $\omega - \epsilon$ is 0.008. In zircon ϵ 1.985, ω 1.926, and $\epsilon - \omega$ 0.059. In calcite the birefringence is high, 0.172, and there is a wide separation of the two rays; while in diamond and other cubic crystals it is nil.

When we come to examine these birefringent crystals under the polarizing microscope, some really beautiful effects are to be observed. Vivid polarization colours are shown when a small thin crystal or a cleavage flake of topaz or muscovite mica is placed between the crossed nicols. It will be found that the crystal becomes dark four times during a complete rotation of the microscope stage. This happens when the vibration-directions in the crystal coincide with those in the two

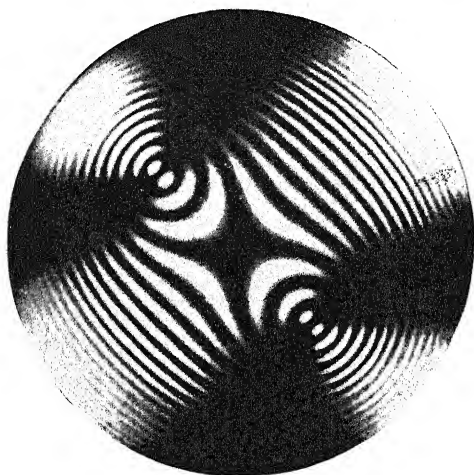
nicol prisms. If this direction of "extinction" (marked by cross-wires in the microscope) is parallel to a prominent edge of the crystal, we have "straight extinction". This will happen, for example, when a crystal of beryl is viewed through a prism face. If the extinction direction is oblique to an edge of the crystal ("oblique extinction"), a measurement of the "extinction angle" will help to decide what kind of crystal is under examination. This examination is made in parallel rays of light passing through the crystal, and the polarization colours are uniformly spread over the whole area of the crystal or flake if this is of the same thickness throughout. If the crystal is wedge-shaped, a series of bands of graded colours is seen.

But when convergent polarized light passes through the crystal (accessories for this are fitted to the microscope), a still more remarkable effect is to be observed. A uniaxial crystal viewed along the optic axis shows a series of concentric brilliantly coloured rings intersected by a black cross (Plate II). A biaxial crystal viewed along the acute bisectrix shows two sets of rings surrounded by a series of brightly coloured lemniscates and ovals and intersected by dark hyperbolic brushes, which as the stage is rotated swing round to form a black cross (Plate II). To see these "optic pictures" or "interference-figures" to the best advantage, it is usually necessary to cut plates from the crystal in the correct direction. They may, however, be readily obtained with cleavage flakes of topaz and muscovite mica, or even sometimes with a little adjustment in a faceted gem-stone. From these interference-figures, even if only a portion of one is seen at the edge of the field of view, the optic sign (positive or negative) of the crystal can be readily determined.

A detailed explanation of the cause of these polarization colours is rather involved and cannot be given here (see textbooks on optics). They are due to the "interference" of waves of light. The vibrations of the

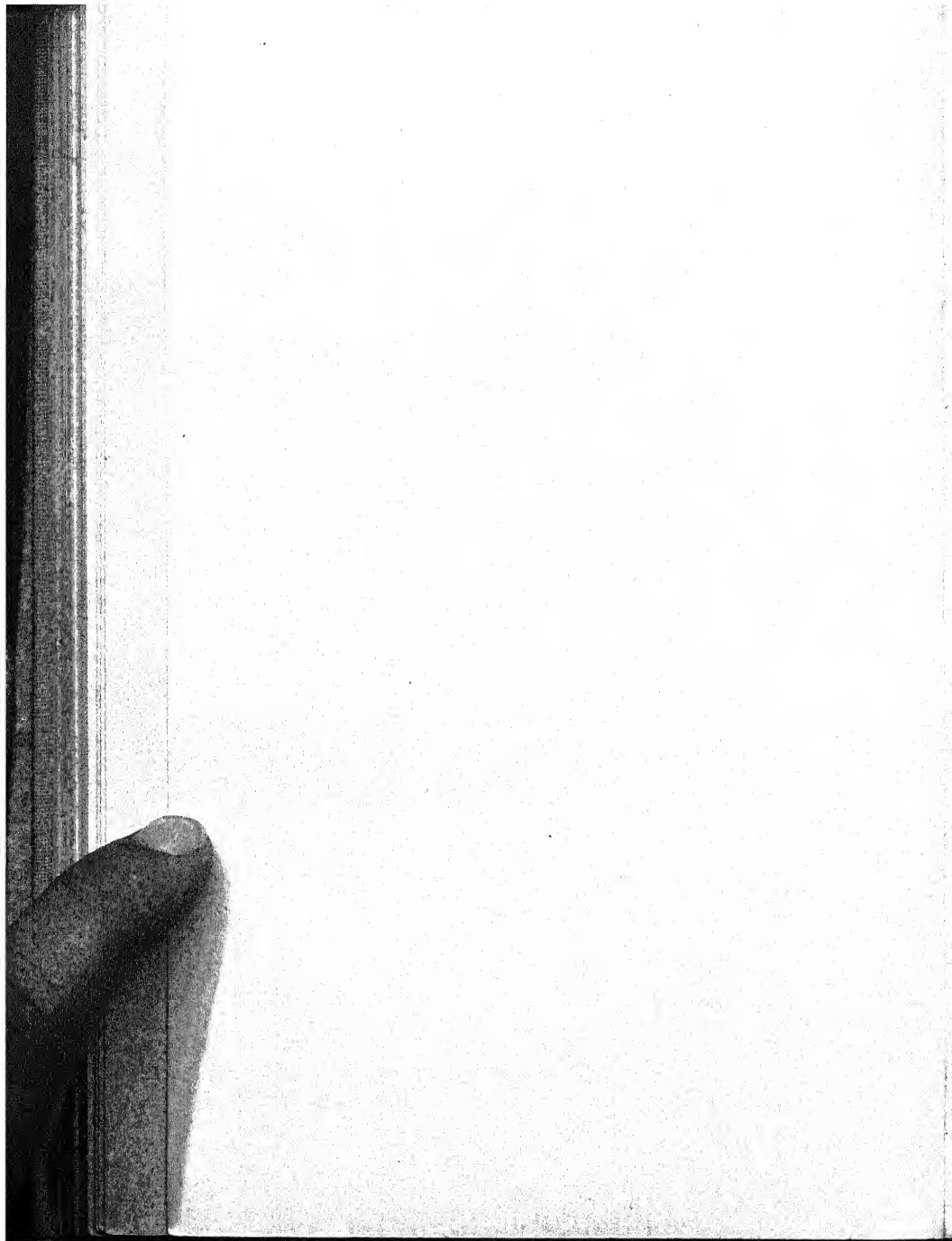


OPTICALLY UNIAXIAL CRYSTAL (BERYL)



OPTICALLY BIAxIAL CRYSTAL (TOPAZ)

INTERFERENCE-FIGURES ("OPTIC PICTURES") SEEN IN CONVERGENT POLARIZED LIGHT
Photographed in yellow sodium-light. In white light the rings are brilliantly coloured



plane polarized light from the lower nicol (polarizer) on passing into the crystal are resolved into two directions at right angles corresponding to the directions along which two refracted rays are permitted to vibrate. Emerging from the crystal and passing into the upper nicol (analyser), these rays are combined again into one plane of polarization. Owing to the different velocities of the two rays inside the crystal, their waves may have acquired a difference in phase, and in the analyser the crest of one wave may coincide with the trough of another. Here we have a balanced tug-of-war and the two waves cancel one another. If these are, say, red waves (depending on the refractive indices for red light in the crystal and on the thickness of the crystal), then red will be cut out and the complementary colour will be seen. When the crystal or cleavage flake is placed on the microscope stage, the observer has not very long to wait for these interference colours to appear. The light is travelling through the crystal at a speed of about a hundred thousand miles a second, and the length of the track need be only a very small fraction of an inch.

From the preceding, perhaps rather involved and confusing account of the optical properties of crystals, it will perhaps at least be realized that crystals have a fine sense of direction. In fact, nearly all the properties of crystals vary with the direction within the crystal. This is a necessary consequence of the symmetrical arrangement of atoms along lines and planes in the crystal-structure (fig. 3), where lines and planes of one or other chemical elements can be traced out. A very striking example of this directional character in crystals is given by *pleochroism*. In the chapter on colour we treated of colour as such, without any regard to direction. But a birefringent crystal may show different colours when viewed in different directions. This is rather an astonishing fact, but quite true. A crystal of cordierite, for example, when viewed through in three

directions at right angles shows in turn the colours Cambridge blue, Oxford blue, and pale yellow. Now what is the real colour of such a crystal, and how can we account for such a strange behaviour?

This is illustrated in fig. 21, which also serves to explain the vibration-directions of waves of light passing through a birefringent crystal. A ray (1) of

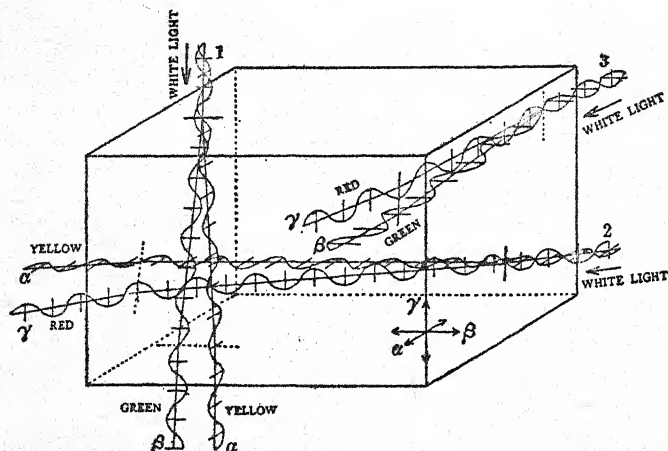


Fig. 21.—Pleochroism. Adventures of white light in a coloured, optically biaxial crystal. A box of conjuring tricks

white light entering through the top surface is refracted into two rays (or rather bundles of coloured rays) the waves of which have vibration-directions parallel to α and β . These vibration-directions are indicated in the corner of the figure; and as they have been drawn all parallel to the rectangular edges of the crystal, this crystal must be an orthorhombic one. Even if the outside ray strikes the surface normally (i.e. at right angles), the two refracted rays cannot preserve this direction. Consequently the rays inside the crystal cannot be quite perpendicular to the directions α and β . It is therefore necessary to resolve the component of a

perpendicular to one ray, and that of β perpendicular to the other. The result is that the rays do not travel through the crystal with exactly the velocity corresponding to the indices of refraction α and β . Now these two rays, each really consisting of a sheaf of rays of different wave-lengths (or colours), as in the singly refracted ray in diamond (fig. 19), are each subjected to a different treatment by the crystal. A coloured crystal may absorb one or more colours from the α -ray, and other colours from the β -ray; and when these emerge from the opposite side of the crystal there will be a difference in the colours remaining in the two sheaves. Similarly, a ray (2) of white light entering the side face is refracted as two sheaves of rays with vibrations parallel to α and γ ; and one (3) entering at the back face will give rise to vibrations parallel to β and γ . Two of these vibration-directions, α and β , have already been involved with the ray (1); but now we have a third, γ , for which the absorption will be again different. The pleochroic colours indicated in the figure are those of andalusite.

Now when this crystal is viewed, even with a microscope, we do not see single rays or bundles of rays, but just a flood of light. The idea of single rays is only for convenience of description and drawing. A drawing showing every single ray would be quite a muddle. The whole crystal is a quivering mass. Neither do we see with the unaided (rude and naked!) eye the "ray-colours" due to the rays α , β , and γ . What we do see are the "face-colours", each consisting of a combination of two ray-colours: on the front face β and γ , on the side face α and γ , and in the bottom face α and β . Uniaxial crystals are limited to two ray-colours, and they are described as "dichroic", while biaxial crystals with three ray-colours are trichroic. The general term pleochroic covers both of these.

The pleochroism of crystals has been explained in some detail because it is an important character of

gem-stones, and one that enables them to be distinguished readily from coloured glass imitations. A very convenient instrument for detecting pleochroism is the *dichroscope*. Two forms of this are shown in the accompanying figures. Fig. 22 shows a handy pocket form containing all the essentials; fig. 23 shows the same tube mounted in a holder with a focusing eye-piece and a holder for the gem-stone. The instrument

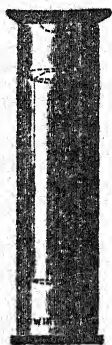


Fig. 22.—Dichroscope,
simple form

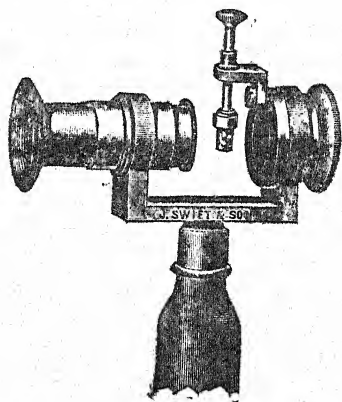


Fig. 23.—Dichroscope with gem holder

consists simply of a special prism of Iceland-spar (doubly-refracting spar) contained in a tube, at one end of which is a square aperture and at the other an eye-piece. Looking through the eye-piece two images of the square aperture are seen side by side. When a pleochroic gem-stone is placed in front of the aperture the two squares will show different colours ("twin colours"), which will be seen to change as the instrument is rotated. These are the ray-colours mentioned above. Pleochroism can also be very readily observed with the polarizing microscope. Only one nicol prism, either the polarizer or analyser, must be in operation, and the crystal is turned round with the stage. The

colours are then seen to change; but the pair of colours are not seen side by side for direct comparison, as in the dichroscope.

No pleochroism will be shown by a uniaxial crystal if this is viewed only in the direction of the optic axis. The maximum effect is seen when the crystal is viewed in a (any) direction perpendicular to the optic axis. Similarly, in biaxial crystals the maximum effects are shown in certain directions (the directions α , β , γ shown in fig. 21).

Although pleochroism is a very useful aid in the determination of gem-stones, yet, like the body colour itself, it is not a constant character, and it may show considerable variations in different specimens of the same kind of stone. The following reference table (p. 66) is to be taken only as a general guide, and not as a "table of constants", and it cannot be made complete.

Now, after all this dose of optics, we come to the really important point. That is the methods for the determination of the refractive index, or the velocity of light, in gem-stones. When a gem is mounted this is often the only decisive test that can be applied for the purpose of determining what the mineral really is. One method that can be applied with transparent faceted gems is the prism method. Here we measure on a goniometer or spectrometer the angle of minimum deviation of a narrow beam of light refracted through two facets. From this angle and the angle between the two facets (which should be about 60° between their normals) the refractive index can be calculated. Another method is the immersion method by immersing minute broken fragments in a series of various liquids of known refractive index. Under the microscope the refractive index of the mineral can be matched with that of one or other of the liquids. This method is of course only applicable when a small fragment can be detached from the stone; and this is always possible

with a rough stone. An approximation may be obtained by immersing the whole stone in such liquids. A colourless stone is almost invisible when immersed in a liquid of the same refractive index.

The third method, and the one most generally applicable in the case of faceted gem-stones, is with the *refractometer* or total reflectometer. This method depends on the principle of the internal total reflection of light, so now the reader will see the reason for the somewhat tedious detail given in an earlier part of this chapter. There are several types and models of this instrument, and as it is of the first importance for gem-testing, three forms specially designed for this purpose are here figured. These consist essentially of a hemisphere of glass of specially high refractive index, about 1.80-1.90 for yellow sodium-light. A *flat* surface of the stone to be tested is placed on the glass hemisphere, and to ensure optical contact a drop of highly refracting liquid (methylene iodide, 1.74) is placed between the two, and the stone *gently* pressed down. A beam of light is sent up through the glass hemisphere to meet the stone, when it is reflected back into the eye-piece of the instrument. A sharp shadow-line is then seen across the field of view. The lighter side of the shadow-line is illuminated by the totally reflected rays; while the darker side is illuminated by rays that have met the stone at an angle less than the critical angle and have been only in part reflected, the main part having passed out through the stone. A glance back at fig. 18 will show that here the stone is playing the part of the air, and the glass hemisphere that of the diamond.

When the examination is made in white light it will be seen that the shadow-line is not perfectly sharp, but is a coloured band; in fact, a very narrow spectrum. This is because the critical angle (dependent on the refractive index) varies with the wave-length of light. The width of this coloured band will give a measure of the dispersion of the stone (p. 45). It is therefore best

when accurate measurements are to be made to use light of one wave-length (monochromatic light), the most convenient being yellow sodium-light.

With an optically isotropic material, such as glass or a cubic crystal, a single shadow-line is seen. But bi-refrangent crystals show two shadow-lines close together. These can usually be seen only in sodium-light: in white light they are coloured and may overlap, producing a wider coloured band. They must not be confused with a third shadow-line due to the highly refractive liquid between the stone and the glass hemisphere.

In optically uniaxial crystals one of the shadow-lines corresponds with the ordinary ray and gives the true value of ω . The other line corresponds with the extraordinary ray, and on all surfaces, except the one perpendicular to the optic axis, it will be seen to move about as the crystal is rotated on the refractometer, reaching a maximum value ϵ in two diametrically opposed positions. In optically biaxial crystals both shadow-lines are due to extraordinary rays and they will shift their position as the crystal is rotated. (On surfaces parallel to each of the three principal optical planes of the crystal one shadow-line, however, remains stationary at its maximum value.) Readings are taken when the shadow-lines are farthest apart, and the two rays can be distinguished and separated with a nicol prism fitted over the eye-piece of the instrument. It is thus possible (though not too easy) to determine with the refractometer the three principal indices of refraction, α , β , and γ , on any chance section of a crystal.

In the more elaborate Abbe model of refractometer (fig. 24), the critical angle is read on the graduated circle which moves with the telescope; and from this angle the refractive index is readily calculated. Or a reference graph may be made by plotting the angles for a few known substances. The smaller Bertrand model (fig. 25) is a convenient pocket instrument; and the refractive index is read directly

on a scale in the eye-piece, ranging from 1.300 to 1.790. In the improved Tully model (fig. 26) the refractive index is also read on a scale, and the glass hemisphere can be rotated. The section (fig. 27) of this instrument shows the path of the ray. It will be noticed that

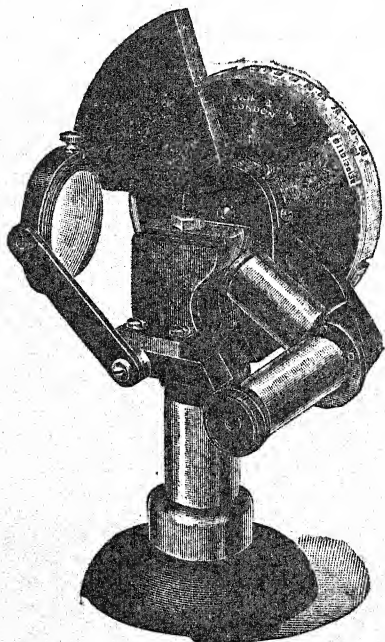


Fig. 24.—Refractometer, Abbe model

change of direction in the path is effected by total reflection inside glass prisms (so in this instrument full use is made of the principle of total reflection).

The convenient refractometer method for the determination of refractive indices has certain limitations. In the first place it can be used only on a *flat* polished surface. This is of course given by faceted gems, but not by cabochon-cut stones. Natural crystal faces can often be used, but they are not always perfectly smooth.

The precaution mentioned above that the stone must be *gently* pressed on the glass hemisphere is important. This highly refractive glass is very soft and may very readily get scratched. After use it should be carefully cleaned with blotting-paper free from any dust. If repolishing is needed this must be done by the maker and the instrument readjusted. Another limitation is that refractive indices higher than that of the glass

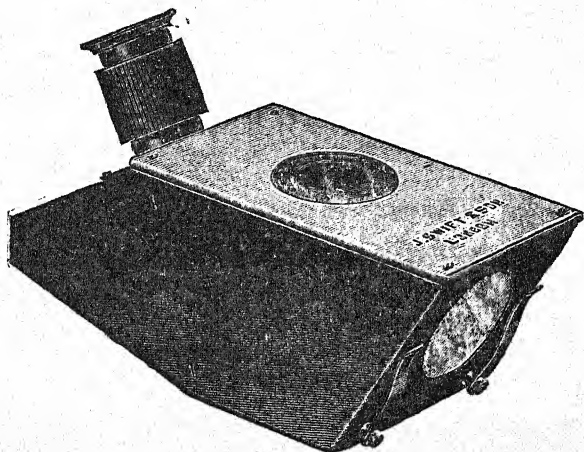


Fig. 25.—Refractometer, Bertrand model

hemisphere (1.80–1.90) cannot be measured, and there are a few gem-stones that come beyond its reach (see the reference table of refractive indices). The refractive index of the liquid placed between the stone and the glass hemisphere has also to be considered. α -Monobromonaphthalene is often recommended, but the refractive index, 1.66, of this comes rather low in the scale. Even methylene iodide with an index of 1.74 cuts out several gem-stones, including the important corundum; but by the addition of certain substances its index can be raised to 1.83. What is really wanted is a hemisphere of diamond (n 2.42). But even that would

cut out diamond itself, and we should have to fall back on some other cubic mineral, e.g. zinc-blende ($n\ 2.43$).

Even with these limitations, the refractometer, like the dichroscope, is an indispensable instrument for the testing of gem-stones. Mention has already been made of the polarizing microscope, but its use requires more experience and some knowledge of scientific mineralogy. But a simple test for double refraction and dichroism can easily be made. A faceted stone should first be placed with the table facet downwards on a microscope

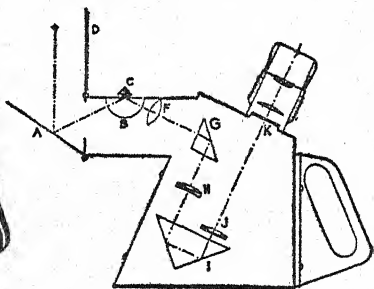
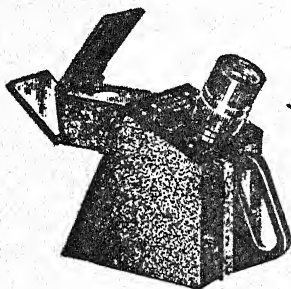


Fig. 26.—Refractometer, Tully model

Fig. 27.—Section of Tully refractometer

A, Reflector. B, Dense glass hemisphere. C, Gem under test. D, Velvet-lined screen. F, H, and J, Lenses. G and I, Prisms. K, Scale.

slide, when a direct view through the stone can be obtained through the culet facet. In other positions it is not always easy to get light through the stone, and an inexperienced observer may mistake stray side reflections for the effects of double refraction. A good method is to immerse the stone in a small bath of liquid of about the same refractive index as that of the stone.

We conclude this chapter with a reference table of refractive indices. The values are given for yellow light. In some species these are fairly constant for the one wave-length, and they are then given to three places of decimals; but in other species, especially those which show isomorphous replacement, there may be a fairly wide range, and here the values are given

to only two places of decimals. The tables usually given in books on precious stones are rather misleading, in that they give the impression that refractive indices have constant values. Other items might have been added to the table. Critical angles of total reflection are easily calculated by the formula $\sin R = 1/n$ from the data given; and the velocity of light in miles per second in any crystal by dividing 186,000 by the refractive index. A comparison of this table (pp. 64-65) with the reference table of specific gravities (p. 26) will show that the several minerals follow in much the same sequence, but with certain exceptions. There must therefore be some connexion between refractive index and specific gravity.

DISPERSION OF THE REFRACTIVE INDICES
OF GEM-STONES *

Fluorite	..	..	0.007	Idocrase	..	..	0.019
Apatite	..	..	0.013	Spinel ..	..	..	0.020
Quartz	..	..	0.013	Olivine	..	..	0.020
Pollucite	..	..	0.014	Pyrope	..	..	0.022
Beryl ..	..	..	0.014	Staurolite	..	..	0.023
Topaz ..	..	..	0.014	Almandine	..	..	0.024
Orthoclase	..	..	0.015	Hessonite	..	..	0.028
Hambergite	..	..	0.015	Willemite	..	..	0.035
Chrysoberyl	..	..	0.015	Diopase	..	..	0.036
Phenakite	..	..	0.016	Zircon ..	..	..	0.039
Euclase ..	..	..	0.016	Diamond	..	..	0.044
Tourmaline	..	..	0.016	Benitoite	..	..	0.046
Scapolite	..	..	0.017	Sphene	..	..	0.051
Cordierite	..	..	0.017	Andradite	..	..	0.057
Danburite	..	..	0.017	Cassiterite	..	..	0.071
Corundum	..	..	0.018	Zinc-blende	..	..	0.156
Kornerupine	..	..	0.018				

* The approximate values here tabulated give the differences between the refractive indices for the Fraunhofer lines B and G in the solar spectrum (red to bluish-violet, wave-lengths 6867 and 4308 Å.). In birefringent crystals a different value is associated with each index ω , ϵ , α , β , γ . Over a different range of wave-lengths the dispersion is of course different; e.g. the value 0.063 for diamond on page 117 is for the extreme red and violet (wave-lengths 7628 and 3969 Å.).

REFRACTIVE INDICES OF GEM-STONES
(for yellow sodium-light)

	Refractive Indices		Birefringence	Optic Sign	Isotropic, Uniaxial or Biaxial
	Least (α , ϵ or ω)	Greatest (γ , ϵ or ω)			
Opal	1.40-1.46		0	0	I
Fluorite	1.434		0	0	I
Silica-glass	1.46		0	0	I
Moldavite	1.48-1.58		0	0	I
Sodalite	1.48		0	0	I
Lazurite	1.50		0	0	I
Pollucite	1.52		0	0	I
Orthoclase	1.52	1.53	0.005	—	B
Amber	1.53-1.54		0	0	I
Cordierite	1.53-1.59	1.54-1.60	0.01	±	B
Oligoclase	1.54	1.55	0.01	—	B
Quartz	1.544	1.553	0.009	+	U
Scapolite	1.54-1.55	1.56-1.57	0.02	—	U
Beryllonite	1.552	1.561	0.009	—	B
Labradorite	1.56	1.57	0.01	+	B
Beryl	1.56-1.59	1.57-1.60	0.006	—	U
Nephrite	1.60-1.62	1.63-1.65	0.03	—	B
Turquoise	1.61	1.65	0.04	+	B
Topaz	1.61-1.63	1.62-1.64	0.01	+	B
Tourmaline	1.62-1.63	1.64-1.65	0.02-0.03	—	U
Danburite	1.630	1.636	0.006	—	B
Andalusite	1.634	1.643	0.009	—	B
Apatite	1.63-1.64	1.64-1.65	0.004	—	U
Jadeite	1.65	1.67	0.02	+	B
Euclase	1.653	1.673	0.02	+	B
Phenakite	1.654	1.670	0.016	+	U
Enstatite	1.65-1.66	1.66-1.67	0.01	+	B
Olivine	1.65-1.68	1.69-1.72	0.04	±	B
Spodumene	1.65	1.67	0.015	+	B
Diopase	1.655	1.708	0.053	+	U
Fibrolite	1.658	1.680	0.022	+	B
Diopside	1.66-1.67	1.69-1.70	0.03	+	B
Kornerupine	1.67	1.68	0.013	—	B
Axinite	1.68	1.69	0.01	—	B
Hypersthene	1.67-1.69	1.68-1.70	0.01	±	B
Willemite	1.69	1.72	0.03	+	U
Idocrase	1.70-1.71	1.71-1.72	0.003	±	U
Kyanite	1.712	1.728	0.016	—	B

REFRACTIVE INDICES OF GEM-STONES—*Cont.*
(for yellow sodium-light)

	Refractive Indices		Birefrin- gence	Optic Sign	Isotropic, Uniaxial or Biaxial
	Least (α , ϵ or ω)	Greatest (γ , ϵ or ω)			
Rhodonite	1.71-1.73	1.73-1.75	0.02	+	B
Epidote	1.72-1.73	1.75-1.78	0.03-0.05	-	B
Spinel	1.72-1.75		0	0	I
Grossular	1.73-1.76		0	0	I
Pyrope	1.73-1.75		0	0	I
Staurolite	1.74-1.75	1.75-1.76	0.01	+	B
Chrysoberyl	1.75	1.76	0.01	+	B
Benitoite	1.757	1.804	0.047	+	U
Corundum	1.760	1.768	0.008	-	U
Almandine	1.77-1.83		0	0	I
Spessartine	1.79-1.81		0	0	I
Andradite	1.82-1.89		0	0	I
Uvarovite	1.84-1.85		0	0	I
Zircon	1.80-1.88	1.81-1.89	0.0.01	+	U
	1.92-1.93	1.97-1.99	0.05-0.06	+	U
Sphene	1.89	1.92-2.00	0.12	+	B
Cassiterite	2.00	2.10	0.10	+	U
Zinc-blende		2.37	0	0	I
Diamond		2.417	0	0	I
Rutile	2.62	2.90	0.28	+	U
Hæmatite	2.94	3.22	0.28	-	U

PLEOCHROIC COLOURS (RAY-COLOURS) OF GEM-STONES

UNIAXIAL CRYSTALS

	Ordinary Ray (ω)	Extraordinary Ray (ϵ)
Red corundum (ruby)	Deep red with violet tinge	Light yellowish red
Blue corundum (sapphire)	Deep blue	Paler greenish blue
Violet corundum	Violet-red	Yellowish red
Green corundum	Yellowish green	Greenish yellow
Green beryl (emerald)	Green	Bluish green
Blue beryl (aquamarine)	Pale blue almost colourless	Rather darker blue
Pink beryl	Pale rose	Bluish rose
Yellow beryl	Pale yellowish green	Bluish green
Red tourmaline	Dark red	Light red
Green tourmaline	Dark green	Light green
Blue tourmaline	Dark blue	Light blue
Red zircon	Columbine-red	Clove-brown
Blue zircon	Blue	Yellowish grey to colourless
Yellow quartz (citrine)	Yellow	Rather paler yellow
Violet quartz (amethyst)	Violet	Greyish violet
Diopase	Dark green	Light green
Idocrase	Yellowish green	Grass-green

BIAXIAL CRYSTALS

	α -ray	β -ray	γ -ray
Chrysoberyl	Red to yellow	Yellow to green	Red
Green chrysoberyl (alexandrite)	Deep red	Orange-yellow	Green
Yellow topaz	Citron-yellow	Honey-yellow	Straw-yellow
Blue topaz	Blue	Pale rose	Colourless
Green topaz	Pale green	Bluish green	Colourless
Olivine	Colourless	Pale green	Oil-green
Andalusite	Yellow	Green	Red
Cordierite	Pale yellow	Pale blue	Dark blue
Staurolite	Yellowish red	Yellowish red	Blood-red
Epidote	Pale yellow	Yellowish green	Green
Pink spodumene (kunzite)	Amethyst	Pale pink	Colourless
Green spodumene (hiddenite)	Bluish green	Emerald-green	Yellowish green
Rhodonite	Pale reddish yellow	Rose-red	Pale reddish yellow
Axinite	Pale green	Dark violet-blue	Cinnamon-brown

CHAPTER VI

Chemical Composition: What Precious Stones are made of

UNTIL the rise of chemistry as an exact science early in the nineteenth century, it was not possible to name and describe any gem-stone correctly. Gem-stones are as much chemicals as drugs and poisons and all the contents of a druggist's shop or a chemist's laboratory. Their true nature depends primarily on their chemical composition. Some slight knowledge of chemistry is therefore necessary for the proper appreciation of the different kinds of gem-stones; whilst for their complete investigation, the aid of a skilled analytical chemist is needed.

Ninety-two different kinds of basic substances are known to chemists. These are the chemical elements which either alone or in combination with one another make up all the different kinds of matter that are known to us. The metal aluminium and the gas oxygen are chemical elements known to everybody. The combination of these two, by burning aluminium in oxygen, gives a white powder of aluminium oxide or alumina, which when crystallized is the mineral corundum, and when this is dyed with small amounts of colouring matter we have ruby and sapphire. Neither aluminium nor oxygen can be split up into any other kinds of matter; but ruby can be split up into aluminium and oxygen. This, however, would not be an economical way of manufacturing aluminium pots

and pans, or of producing cylinders of oxygen for the restoration of life. Another familiar example of a chemical compound is given by common salt, which consists of a combination of the light, readily combustible metal sodium and the heavy, suffocating gas chlorine, these being chemical elements. Salt can be taken with impunity, but it would be fatal to take its components separately.

In the reference table given below (p. 74) are listed the chemical elements which enter into the composition of gem-stones. As far as the essential constituents are concerned, these are limited to quite a few of the more common elements. Diamond is the only gem-stone which consists of a single element (carbon). All others are chemical compounds, and all of them (except fluorite) contain oxygen. Other more important essential elements are silicon, aluminium, beryllium, iron, magnesium, &c. By the essential constituents we mean those that build up the basic material itself, apart from accidental impurities and traces of colouring matter, which are always present in gem-stones although in minute quantities. Even the purest diamond when burnt will leave a very small amount of ash. If we included all the unessential constituents present as mere traces, our list would no doubt extend to the complete number of ninety-two elements, for, after all, chemists have to go to minerals for their crude materials. Spectroscopic analysis shows the presence of a surprising number of rare elements in gem-stones. But this is a special study, which has some bearing on the problems of origin of the stones and the nature of their colouring matters.

In the reference list of elements given at the end of this chapter are also added their chemical symbols and atomic weights. These require some explanation. Two atoms of aluminium combine with three atoms of oxygen to form alumina, corundum, or ruby. The composition of the resulting compound is briefly ex-

pressed by the chemical formula Al_2O_3 , which represents a molecule of alumina. An atom is the smallest possible individual amount of each element. The atomic weights give the relative weights of the different kinds of atoms compared with that of the hydrogen atom taken as unity. For example, an atom of aluminium is 27 times heavier than an atom of hydrogen. The actual weight of an atom of hydrogen is of course an extremely small amount; it is given as 1.64×10^{-24} gram, that is, twenty-three noughts after the decimal point, 0.00 ... 164 (to reduce to carats multiply by five). Further, the atomic weights express the amounts by weight of each element present in a compound. For example, 54 ($= 27 \times 2$) carats or tons of aluminium and 48 ($= 16 \times 3$) carats or tons of oxygen will yield 102 carats or tons of ruby; and conversely from 102 tons of ruby there could be manufactured 54 tons of aluminium pots and pans. Similarly, 23 parts of sodium combine with 35.5 parts by weight of chlorine to give sodium chloride (NaCl) or rock-salt. In the rock-salt crystal, the sodium and chlorine atoms are situated alternately at equal distances apart along the lines of a simple cubic lattice (fig. 3). Such a structure is known as the "rock-salt structure". There are no separate NaCl molecules, but the whole structure extended indefinitely contains equal numbers of sodium and chlorine atoms.

The table (p. 74) has been made fairly complete, and is intended merely for reference. Some of the elements listed are of only minor importance so far as the familiar gem-stones are concerned. Twenty-six (of the 92) elements are listed—just as many as there are letters in the alphabet. By combining these elements (or letters) in different ways to form compounds (or words) we obtain an almost endless variety. In the first place, oxygen is capable of combining with any of the other elements in the list (except fluorine), yielding oxides. For example, aluminium oxide or alumina (Al_2O_3),

silicon oxide or silica (SiO_2), calcium oxide or lime (CaO), magnesium oxide or magnesia (MgO), the iron oxides, ferric oxide (Fe_2O_3) and ferrous oxide (FeO), phosphorus pentoxide (P_2O_5), carbon dioxide (CO_2), and hydrogen oxide or water (H_2O). Some of these are basic oxides and others are acid oxides. Water is neutral and may combine with the basic oxides to give hydroxides, e.g. $\text{CaO} + \text{H}_2\text{O} = \text{CaO}_2\text{H}_2$, calcium hydroxide or slacked lime. Or it may combine with the acid oxides to give acids, e.g. $\text{CO}_2 + \text{H}_2\text{O} = \text{H}_2\text{CO}_3$, carbonic acid; $\text{SiO}_2 + \text{H}_2\text{O} = \text{H}_2\text{SiO}_3$ or $\text{SiO}_2 + 2\text{H}_2\text{O} = \text{H}_4\text{SiO}_4$, silicic acids; $\text{P}_2\text{O}_5 + 3\text{H}_2\text{O} = 2\text{H}_3\text{PO}_4$, phosphoric acid. Now a basic oxide may combine with an acid oxide, or an hydroxide with an acid, to give what chemists call oxygen salts. For example, $\text{CaO} + \text{CO}_2 = \text{CaCO}_3$, which is the composition of pearls and coral; $\text{Al}_2\text{O}_3 + \text{SiO}_2 = \text{Al}_2\text{SiO}_5$, andalusite, kyanite, and fibrolite; $\text{MgO} + \text{SiO}_2 = \text{MgSiO}_3$, enstatite; $2\text{MgO} + \text{SiO}_2 = \text{Mg}_2\text{SiO}_4$, olivine; $3\text{MgO} + \text{Al}_2\text{O}_3 + 3\text{SiO}_2 = \text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$, pyrope; $\text{CuO} + 3\text{Al}_2\text{O}_3 + 2\text{P}_2\text{O}_5 + 9\text{H}_2\text{O} = \text{H}_{18}\text{CuAl}_6\text{P}_4\text{O}_{29}$, turquoise, a complex molecule containing 58 atoms and rather doubtful. These salts are known as carbonates, silicates, and phosphates.

Alumina may act also as an acid oxide (in the above example when combined with silica it acted as a basic oxide); e.g. $\text{MgO} + \text{Al}_2\text{O}_3 = \text{MgAl}_2\text{O}_4$, spinel; and $\text{BeO} + \text{Al}_2\text{O}_3 = \text{BeAl}_2\text{O}_4$, chrysoberyl. These salts are known as aluminates. There is still another class of salts, known as haloids, in which chlorine or fluorine may combine directly with a metal; e.g. $\text{Na} + \text{Cl} = \text{NaCl}$, sodium chloride or rock-salt, and $\text{Ca} + \text{F}_2 = \text{CaF}_2$, calcium fluoride or fluorspar (fluorite).

So we can keep on building up atoms to form complex molecules, much the same as with word building. When we come to tourmaline, which may contain a dozen or more different elements, a very complex and uncertain formula is arrived at. But our trouble does

not end here. All the formulæ given above only approximately represent the chemical composition of the different minerals. For example, olivine always contains a variable amount of iron (in gem material about 10% of ferrous oxide, FeO), and as this increases in amount, there may be a gradual passage from Mg_2SiO_4 to Fe_2SiO_4 . This is known as isomorphous (equal form) replacement, and it is a principle of fundamental importance in mineral chemistry. The "mixed crystals" of the series all have the same geometrical form with only very slight differences in the angles between corresponding faces. The reason for this replacement is that the atoms of ferrous iron are of very nearly the same size as those of magnesium, and they can thus take their place as interlopers in the lattice structure built up primarily by the magnesium atoms together with silicon and oxygen. There are several other isomorphous replacements of this kind in minerals; e.g. ferric iron taking the place of aluminium. The garnet group affords a striking example, as will be explained in more detail in a later chapter. Natural spinel usually contains some silica, whilst artificial spinel often contains an excess of alumina over that required by the formula MgAl_2O_4 . Such replacements of Al_2O_3 by SiO_2 and of MgAl_2O_4 by Al_2O_3 are explained by recent X-ray work on the structure of crystals.

A scientific classification of gem-stones must be based on their chemical composition; since on this, together with the crystalline structure, all their other characters depend. Any other classifications based on colour, importance or rarity are quite arbitrary. Here it will be convenient to introduce another reference table giving a list of gem-stones under the several chemical divisions, and with the approximate chemical formula of each stone (p. 73). But this order will not be followed in later descriptive chapters.

It is of some interest and importance to know what different kinds of gem-stones are composed of; but,

as a rule, this knowledge cannot be applied for the purpose of finding out what kind of stone we have in hand. Chemical tests involve the destruction of the material and are therefore of little or no practical use in the case of gem-stones. A chemical test for diamond, for instance, would mean the burning of the material and collecting the resulting carbon dioxide. We must therefore rely on physical tests for purposes of determination. If, however, we should meet an entirely new kind of gem-stone, of which rough material is available, a complete chemical analysis must of course be made for a thorough investigation by mineralogical methods.

Most gem-stones, by the very reason of their hard and durable nature, are resistant to acids. Pearls and coral, consisting of calcium carbonate, show a brisk effervescence when touched with a drop of dilute hydrochloric acid (according to Cleopatra, with vinegar or acetic acid); but this is a risky test, as the surface polish is destroyed. Turquoise and apatite are soluble in hydrochloric acid, and a minute fragment on a microscope slide will give the reaction for a phosphate.

CHEMICAL CLASSIFICATION AND
FORMULÆ OF GEM-STONES

ELEMENTS

Diamond C

HALOIDS

Fluorite CaF_2

OXIDES

Quartz SiO_2 Silica-glass SiO_2 Corundum Al_2O_3 Rutile TiO_2 Cassiterite SnO_2 Hæmatite Fe_2O_3

HYDROXIDES

Opal $\text{SiO}_2 \cdot x\text{H}_2\text{O}$

ALUMINATES

Spinel MgAl_2O_4 Chrysoberyl BeAl_2O_4

CARBONATES

Pearl CaCO_3 Coral CaCO_3

BORATES

Hambergite $\text{Be}_2(\text{OH})\text{BO}_3$

Rhodizite Al, Be, Cs, etc.

SILICATES

Enstatite MgSiO_3 Bronzite $(\text{Mg, Fe})\text{SiO}_3$ Hypersthene $(\text{Fe, Mg})\text{SiO}_3$ Rhodonite MnSiO_3 Diopside $\text{CaMg}(\text{SiO}_3)_2$ Spodumene $\text{LiAl}(\text{SiO}_3)_2$ Jadeite $\text{NaAl}(\text{SiO}_3)_2$ Nephrite $\text{H}_2\text{Ca}_2\text{Mg}_5(\text{SiO}_3)_8$ Beryl $\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$ Benitoite $\text{BaTi}(\text{SiO}_3)_3$ Pollucite $\text{H}_2\text{Cs}_4\text{Al}_4(\text{SiO}_3)_9$ Olivine $(\text{Mg, Fe})_2\text{SiO}_4$ Phenakite Be_3SiO_4

SILICATES—Continued

Willemite Zn_2SiO_4 Diopase H_2CuSiO_4 Zircon ZrSiO_4 Topaz $\text{Al}(\text{F, OH})_2\text{SiO}_4$ Danburite $\text{CaB}_2(\text{SiO}_4)_2$ Grossular $\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$ Pyrope $\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$ Almandine $\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$ Andradite $\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$ Spessartine $\text{Mn}_3\text{Al}_2(\text{SiO}_4)_3$ Uvarovite $\text{Ca}_3\text{Cr}_2(\text{SiO}_4)_3$ Sodalite $\text{Na}_4\text{Al}_3\text{Cl}(\text{SiO}_4)_3$ Lazurite $\text{Na}_5\text{Al}_3\text{S}_3(\text{SiO}_4)_2$ Axinite $\text{HCa}_2\text{BaAl}_2(\text{SiO}_4)_3$ Andalusite Al_2SiO_5 Kyanite Al_2SiO_5 Fibrolite Al_2SiO_5 Euclase HBeAlSiO_5 Sphene CaTiSiO_5 Orthoclase KAlSi_3O_8 Labradorite $\begin{cases} m\text{NaAlSi}_3\text{O}_8 \\ n\text{CaAl}_2\text{Si}_2\text{O}_8 \end{cases}$ Scapolite $\begin{cases} m\text{Na}_4\text{Al}_4\text{ClSi}_3\text{O}_8 \\ n\text{Ca}_4\text{Al}_2\text{Cl}_2\text{Si}_2\text{O}_8 \end{cases}$ Epidote $\text{HCa}_2\text{Al}_2\text{Si}_2\text{O}_{13}$ Idocrase $\text{H}_2\text{Ca}_4\text{Al}_3\text{Si}_5\text{O}_{18}$ Serpentine $\text{H}_4\text{Mg}_3\text{Si}_2\text{O}_9$ Cordierite $\text{H}_2\text{Mg}_4\text{Al}_5\text{Si}_{10}\text{O}_{37}$ Staurolite $\text{HFe}_2\text{Al}_3\text{Si}_4\text{O}_{24}$ Tourmaline $\begin{cases} (\text{Mg, Fe, Ca, Na,} \\ \text{Li, H, F})_{11} \\ \text{Al}_3\text{B}_2\text{Si}_4\text{O}_{21} \end{cases}$

PHOSPHATES

Turquoise $\text{H}_{18}\text{CuAl}_6\text{P}_4\text{O}_{29}$ Beryllonite NaBePO_4 Apatite $\text{Ca}_5\text{FP}_3\text{O}_{12}$

ORGANIC HYDROCARBONS

Amber $\text{C}_{10}\text{H}_{16}\text{O?}$

Jet —

CHEMICAL ELEMENTS PRESENT IN GEM-STONES

Element	Symbol	Atomic Weight	Gem-stones
Aluminium	Al	27	Corundum (ruby and sapphire), spinel, chrysoberyl, beryl (emerald), topaz, tourmaline, garnets, feldspars, staurolite, andalusite, kyanite, epidote, idocrase, spodumene, jadeite, and several other silicates; turquoise.
Barium	Ba	137.4	Benitoite.
Beryllium	Be	9	Beryl (emerald), chrysoberyl, phenakite, euclase, beryllonite, hambergite, rhodizite.
Boron	B	10.8	Tourmaline, axinite, danburite, hambergite, rhodizite, kornerupine.
Cæsium	Cs	133	Pollucite, cæsium-beryl, rhodizite.
Calcium	Ca	40	Pearl, coral, fluorite, epidote, idocrase, garnet (hessonite), nephrite, labradorite, sphene, apatite.
Carbon	C	12	Diamond, pearl, coral.
Chlorine	Cl	35.5	Sodalite, scapolite.
Chromium	Cr	52	Uvarovite. (Colouring agent in ruby and emerald.)
Copper (cuprum)	Cu	63.6	Turquoise, diopside.
Fluorine	F	19	Topaz, fluorite, apatite; small amounts in some silicates.
Hydrogen	H	1	Opal; small amounts in tourmaline, topaz, and some other silicates.

CHEMICAL ELEMENTS PRESENT IN GEM-STONES

—Continued

Element	Symbol	Atomic Weight	Gem-stones
Iron (ferrum)	Fe	55.8	Hæmatite, garnets, staur- olite, and subsidiary amounts in several sili- cates, olivine, tourma- line, &c.
Lithium	Li	7	Spodumene; small amounts in some tourmalines and beryls.
Magnesium	Mg	24.3	Spinel, olivine, enstatite, pyrope, diopside, neph- rite, and some other silicates.
Manganese	Mn	55	Rhodonite, spessartine.
Oxygen	O	16	All gem-stones except dia- mond and fluorite.
Phosphorus	P	31	Turquoise, apatite, beryl- lonite.
Potassium (kalium)	K	39	Moonstone, Amazon-stone; small amounts in some tourmalines and beryls.
Silicon	Si	28	Quartz, opal; all silicates.
Sodium (natrium)	Na	23	Sodalite, oligoclase, jade- ite, beryllonite; small amounts in some tour- malines and beryls.
Sulphur	S	32	Lapis-lazuli.
Tin (stannum)	Sn	118.7	Cassiterite.
Titanium	Ti	48	Sphene, benitoite, rutile.
Zinc	Zn	65.4	Willemite, zinc-blende.
Zirconium	Zr	91.2	Zircon.

CHAPTER VII

Geological Occurrence and Origin of Precious Stones

THE connoisseur who admires things antique will find something really old in gem-stones. Many of them were formed in the oldest unfossiliferous rocks of the earth's history, before the advent of life. This was in the pre-Cambrian or Archæan period of geology, dating back about a thousand million years or more. But it does not follow that gem-stones are always to be found in such rocks. Perhaps the largest area of their exposure on the earth's surface is in the great pre-Cambrian shield of Canada, where much gold has been found, but few minerals of gem value. Nor must it be supposed that they are found only in these oldest rocks. They are found in rocks of all geological periods, and no doubt they are still being formed at the present day deep down in the earth's crust. They are certainly being formed at the present day in the chemist's laboratory and in gem factories.

No books on the true history of precious stones, from a geological point of view, or on their genesis from a mineralogical point of view, have yet been written. There are many interesting points and unsolved problems—but this chapter must be kept within limits. One interesting period is that of the Cretaceous, a matter of only some sixty million years ago (but quite sufficient to satisfy any antique dealer). In rocks of this age are found the Australian opals and the remarkable deposits in limestone of emeralds in Colombia.

At this period also diamonds were erupted into the volcanic pipes of South Africa, although it is evident that the diamonds themselves belonged to some still earlier period.

The many different kinds of rocks of which the earth's crust is composed may be conveniently grouped into three main classes—igneous, sedimentary, and metamorphic. This grouping is based on their mode of origin without any reference to their age. Representatives of each class are to be found amongst the rocks of all geological periods or ages.

In our study of precious stones we are not concerned with theories of the origin of the earth, which is supposed at one time to have been a blob of gas gradually cooling to a drop of liquid. With further cooling a thin crust was frozen on the surface. This was the first solid igneous rock, and it no doubt contained some precious stones. But it was much too hot and the crust too unstable for anybody to be there to find them.

Igneous rocks consist of silicate minerals frozen from the molten state, and they are of many different kinds. They show wide ranges in their chemical composition, in the minerals of which they are composed, and in their structures and textures. The detailed study of these matters we must leave to the petrologist, though they have important bearings on the origin of precious stones. Two main types of igneous rocks are to be distinguished—volcanic and plutonic, or extrusive and intrusive. The former have consolidated from the molten lava poured out on the earth's surface by volcanoes; the latter from lava that has been intruded along crevices in the earth's crust, or consolidated in the cistern of molten rock (magma) beneath a volcano or potential volcano.

Volcanic rocks have cooled quickly under ordinary pressure, and the acid varieties (i.e. richer in silica) may sometimes consolidate as a glass. This volcanic glass is called obsidian, and is sometimes cut as a gem-

stone, especially when it shows a coloured silky sheen. Usually, however, minute crystals have commenced to grow, and the resulting rock is fine grained and stony, of which basalt is an example. Beautiful sky-blue crystals of haüyne are sometimes found in such rocks; and occasionally small crystals of sapphire and red zircon from which a few gems have been cut. The latter, however, were probably not formed in this rock, but caught up by the lava from some older rock.

Plutonic rocks, having cooled much more slowly and under pressure beneath the surface, are more coarsely grained; and the different minerals of which they are composed can be readily distinguished. Such rocks include granite, syenite, peridotite, and several other kinds. In granite we may find good crystals of beryl, topaz, zircon, and other gem minerals; in syenite, crystals of corundum (ruby and sapphire) and zircon; while peridotite, as the name implies, is essentially an olivine-rock, and this may also contain corundum. In such cases the minerals have grown in the rock (the mother-rock) and they are described as *primary* minerals. They are, however, at the same time *accessory* or *accidental* minerals; for, as a rule, they are present in only small amount compared with the rock-forming minerals that make up the bulk of the rock. Occasionally, however, they may be present in larger amount, and we may have such a rock as a corundum-syenite, in which corundum is an essential constituent. Some bodies of plutonic rocks are of enormous size, their outcrop at the earth's surface covering hundreds of square miles. The whole of Dartmoor, for example, is just the top of one large boss of granite; how far it extends downwards is not known. Gem minerals found in the Dartmoor granite include corundum, spinel, topaz, zircon, garnet, tourmaline, andalusite, cordierite, fibrolite, sphene; but unfortunately here only as crystals of microscopic size.

During the later stages in the consolidation of the

rock in these large cisterns the residual mother-liquor, rich in water (under great pressure of course, and above the critical temperature), is squeezed out along crevices in the rock already formed or in the surrounding country-rocks. This material gives rise to a rock more coarsely crystallized than the normal rock, and known as pegmatite. It often has the form of huge sheets or lenses, which are well known as pegmatite dikes or veins. Now, it is just in these pegmatite dikes that most gem minerals are found, together with a great variety of other minerals of special interest to mineralogists, including radioactive minerals from which radium can be extracted. It seems that all the materials for the formation of gem-stones and other rare minerals are contained in these rock juices—and that the gravy is the thing to go for when searching for treasure. Cavities are often met with in pegmatites; they were no doubt formed as steam cavities, and they are sometimes of considerable size. Here crystals have been able to grow freely; and such cavities may be lined with fine crystals of a variety of minerals, including beryl, topaz, quartz, tourmaline, amazon-stone, &c. *Attached* crystals of this kind can readily be broken away whole from the supporting matrix. Other crystals are *embedded* in the surrounding solid rock, and these are not so easily extracted. The embedded crystals of pegmatites may reach enormous dimensions. A crystal of felspar in a Norwegian pegmatite, estimated to weigh 200 tons, and one of spodumene weighing 90 tons in South Dakota, are records for the size of crystals; but these were not of gem quality. Pegmatites are extensively quarried for felspar and quartz, which are used in the manufacture of porcelain; and also for mica. A high-grade Canadian felspar known as "dental spar" gives an extra fine porcelain for the manufacture of false teeth. Gem minerals are sometimes collected in these felspar quarries; and at times the pegmatites have been quarried solely for this purpose.

Farther away from the main igneous mass we may find the pegmatite veins grading into quartz veins. These often carry gold (gold quartz) as well as some gem minerals. Or we may have mineral veins carrying ores of various metals, accompanied by another suite of gem minerals, such as topaz, tourmaline, garnet, and amethyst.

Some of these large bodies of plutonic rocks, formed deep down in the earth's crust, we now find exposed at the surface, and we then have access to the precious stones embedded in them. This is one of the fortunate results of the fact that our earth is provided with an atmosphere and a hydrosphere, which under the influence of the sun's rays are in a state of continual commotion, wearing down the solid rocks by a process known to geologists as denudation. The wearing and breaking down of rocks is familiar to everybody, even if they are not geologists. This is effected by rain, frost, ice, changes of temperature, wind and waves, chemical action in the presence of water, and the growth of plants. The broken fragments are especially conspicuous when seen in scree and at the base of cliffs; while all the soil on the surface is due to the same causes. This fragmentary material is transported to lower levels by running water, and is eventually deposited in the sea. The process is of course a very slow one. Only the top of the Dartmoor granite mass is now exposed after a period of about two hundred million years.

Sedimentary rocks are those formed by the sedimentation in water of the debris resulting from the denudation of pre-existing rocks. They include clay, shale, sandstone, limestone and chalk, conglomerate, &c., which are rocks familiar to everybody (conglomerates are consolidated pebble beds). Only in a few exceptional cases do these rocks contain any gem material that was formed contemporaneously with the rocks themselves. For example, jet in shale of Liassic age repre-

sents a fossilized wood; and amber in sands of Tertiary age is a fossil resin. Nevertheless, sedimentary rocks do contain a large variety of gem minerals of detrital origin, and another series of minerals of secondary origin; the former deposited at the same time as the rocks themselves and the latter of later formation (p. 82).

When sedimentary rocks are crushed and powdered and their constituent minerals separated by agitation in water and with the aid of heavy liquids, a small concentrate of heavy minerals is obtained. A microscopical examination of this concentrate will reveal the presence of minute crystals and fragments of practically all gem minerals. These have of course been derived with the other debris from pre-existing rocks, and they are described as detrital minerals. The diamonds of India and Brazil, and also the rare diamonds of the gold-bearing rocks of the Witwatersrand, are detrital minerals found in sedimentary rocks (conglomerates) of pre-Cambrian age; and they must have been derived from still older rocks which would add another era to our approximate estimate of a thousand million years ago. In Belgian Congo and Angola detrital diamonds are found in conglomerates of the much later Triassic period of geology.

Metamorphic rocks were originally either igneous or sedimentary rocks which have had their characters drastically changed by the effects of great pressure and heat while buried deep in the earth's crust, to be exposed later at the surface by denudation. A fresh suite of minerals, very often gem minerals, has thereby been regenerated from the minerals that composed the original rocks. Since most gem minerals (notably corundum and garnets) are characterized by a high density, they occupy less space than rock-forming minerals of lower density. Under the influence of enormous earth pressures, with accompanying high temperature and the presence of water, the conditions

are therefore specially favourable for the formation of such minerals ("stress minerals") by the resorting of the chemical constituents of the rock. In such rocks as gneiss and schist we often find garnets, kyanite, fibrolite, staurolite, corundum, beryl, &c.; and in slates we find andalusite and cordierite. Under such circumstances these minerals will only be met with as embedded crystals.

All rocks are traversed by crevices and contain cavities of various kinds; and with the percolation of ground-water or the water of hot springs, containing various substances in solution in small amounts, important secondary changes are brought about with the production of secondary minerals. The materials for the formation of these secondary minerals may be leached out from the rock itself, or they may be supplied from some outside source; or the new minerals may result from an interaction of these two sets of material. The exact nature of such processes is not yet well understood. Volcanic rocks are usually of a porous nature (as witness pumice stone) due to the presence of steam cavities. In ancient lavas which have been buried under a rock cover we find that the cavities have become filled with mineral matter. This is the source of the best agates and amethysts. The Hungarian opal and the Persian turquoise are secondary minerals in volcanic rocks of Tertiary age. On the other hand, the Australian opals are of secondary formation in sandstone and siliceous ironstone of Cretaceous age, and the turquoise of Sinai in sandstone of Lower Carboniferous age. A very puzzling case is the occurrence of the best quality of emeralds in limestone of Cretaceous age in Colombia. The gneissic and schistose rocks of the Alps, which have been much crumpled and disturbed by earth movements in the processes of mountain building, contain many crevices lined with beautifully crystallized minerals. This "Alpine type" of mineral veins yields rock-crystal, smoky-quartz, and the best gem-quality sphene.

We see from the above that one and the same mineral may be formed in nature by more ways than one. Corundum and beryl, for example, may be either of igneous or metamorphic origin, and the latter (as emeralds) also of secondary origin; while quartz and its many varieties may be formed under very varying conditions. A study of the modes of occurrence and origin of minerals will give some clues for their artificial reproduction. But, strange to say, the most successful process for the artificial production of precious stones (corundum and spinel) from a fine spray of molten alumina is not copied from nature.

Now after taking the pains to write this discourse upon rocks and the precious stones they *may* contain, we must nevertheless inform the patient reader that only exceptionally are gem-stones obtained from such rocks. Any stones of good gem-quality are very sparingly and sporadically distributed through the solid rock. It would not be worth while to pull down a whole mountain and crush the rock on the chance of finding a handful of gems. Fortunately, this work has already been done for us by nature, working slowly but surely through countless ages by the processes of denudation, as already mentioned. The disintegrated material is transported by running water, first along channels and rills on the hillside, and then into brooks and streams. There is much banging and rubbing, and the material is further broken down; and an important sorting action now comes into play. The smallest, lightest, and flaky particles are carried farthest, and are eventually deposited in the quieter waters of a lake or in the sea as mud and clay. Materials of greater specific gravity (see the reference table at the end of Chapter III) are not carried so readily as the bulk of the lighter material, which consists mainly of quartz. In this way there may be under certain circumstances a concentration of the heavier minerals, such as gold and gem-stones. These may be found in pockets worn

in the bed-rock by the grinding action of pebbles, in crevices, or on the upstream side of rock rifts crossing the stream; or, again, in patches of coarser gravel. Deposits of mud, silt, sand, and gravel formed by river action, and covering the whole of the flood plain of the valley bottom, are known as alluvial deposits. It is here that most gem-stones are found; but, of course, only along those streams that have drained from areas where gem-bearing rocks are exposed. Gravels are abundant and well known in the Thames valley, but a search here for gem-stones would be in vain, since all the materials have been derived from younger sedimentary rocks.

The gem-stones found in these alluvial deposits usually show signs of wear, to an extent depending on the distance they have been rolled in streams from their parent-rock. If found quite near the source, the crystals may be sharp and clear, as shown by some crystals of spinel from Burma. More often the edges of the crystals are rounded and the faces dulled; and frequently they have the form of well-rounded pebbles. The wear and tear during transportation has made a further selection in the quality of the material. Flawed and cracked material and aggregates of crystals have been broken up, and only the more perfect crystals have withstood the racket. For this reason the best quality gem material is usually that found in alluvial deposits, though often only as small crystals or pebbles. A water-worn crystal weighing 29 pounds of clear colourless topaz from Brazil, and a well-rounded boulder weighing 1156 pounds of bright green nephrite (jade) from Siberia, are exhibited in the mineral collection of the British Museum.

In the majority of cases the gem-stones in alluvial deposits have been first found when panning the streams for gold. And by tracing the pebbles up the course of the stream, the prospector has often been able to locate the mother-rock. Alluvial gold is of very

wide distribution, but usually only quite small in quantity (nice little nuggets have been found in Cornwall, Wales, Scotland, and Ireland); and in the eager and frantic search for the precious metal it is quite likely that gem-stones have often been overlooked. When well worn and rounded with dull surfaces, gem-stones often do not look very different from ordinary pebbles. A person acquainted only with the appearance of cut gems would not recognize the stones in their rough state. Hence the importance of some knowledge of the mineralogy and geology of gem minerals.

The geographical distribution of gem-stones is quite accidental. It is not limited by political boundaries, but depends solely on the kinds of rocks that are exposed at the surface. Since they more often occur in the older and harder rocks, they are consequently usually found in mountainous districts. In former times most gem-stones came from the East, and the term "Oriental" still survives for the finer quality stones. It was once thought that they were generated only in hot climates. This is quite true, but it is the still hotter climate deep down in the earth's crust, rather than at the surface, that is favourable for the growth of crystals. A booklet on the occurrence and production of gem-stones in different countries is issued by the Imperial Institute, London, in the series on the mineral industry of the British Empire and foreign countries.

CHAPTER VIII

Mining of Precious Stones

AS pointed out in the last chapter, most gem-stones are obtained from alluvial deposits. They are, however, not found in the more extensive deposits in the lower reaches of large rivers, but only in those of smaller extent and volume in the upper reaches, which are usually in the deep valleys of mountainous districts. This is because of the sorting action effected by running water, according to the specific gravity of the transported material, the heavier stones being left nearer their source in the mother-rock. On this account, alluvial mining can usually be carried on only by small gangs working independently, and the work is usually done by natives using very primitive methods.

When working in the stream itself, the only tool required is a prospector's pan. This is a shallow, circular dish, one or two feet in diameter, with gradually sloping sides rounding to the bottom (like a slice cut from a sphere), and made of metal, wood, or woven fibres. The gem-washer, standing in the stream, scoops up gravel from the bottom with his (or often her) pan. The pan, while still under water, is then given a circular and up and down motion, being at the same time slightly tilted. The finer dirt and particles pass out over the edge of the pan, and the gold and heavy minerals work their way to the bottom beneath the lighter pebbles. The latter may be helped away with the hand; or the whole panful is turned out upside down on the ground, when the gem-stones are

picked out at the top, and the remainder sorted over by hand with a quick eye. Gem-bearing gravel dug from shallow pits on the banks of the stream is carried down to the stream and treated in the same manner.

By a more advanced method, the gravel is washed and sorted in water running down an inclined trough or sluice provided with riffles. Better still is the "jig" or "jigger", which is in common use for separating metallic ores from the gangue or rocky matrix. This consists of a strong box open at the top and with a perforated bottom which is immersed in a deep trough of flowing water. The box is violently jiggled up and down and wriggled sideways; and there may be a long battery of these worked by machinery—and raising a racketing din. In larger washing plants, as at the Kimberley diamond mines, the material is first washed from mud in large circular pans provided with rotating arms, before it is passed to the jigs. When dealing with large quantities of material, the bulk of which has to be delivered on the waste heaps, the feed to the machinery is automatic on travelling belts.

These methods can, of course, only be used where a plentiful supply of water is available. In the early days of the "dry diggings" on the dry plateau where Kimberley now stands with the Vaal river twenty miles away, the diamond-bearing ground had to be screened and winnowed. At the present time, the water for washing is pumped from the deep mines. At isolated spots in desert regions, this method is still in use with a small winnowing machine; and also the method of dry blowing by pouring the material from one dish to another, when the wind carries away the dust and finer and lighter particles, leaving the coarser material to be sorted over by hand.

The pits dug in alluvial deposits are usually quite small with very primitive arrangements for supporting the sides and bailing out water. Only occasionally, as in the Burma Ruby Mines, have more efficient methods,

dealing systematically with large amounts of material, been in use. Washing down material on a hillside with a powerful jet of water (hydraulic) has only rarely been adopted. Large mechanical dredgers, as used for dredging gold and tin ore in rivers, have not been used for the recovery of gem-stones. The course of the Vaal river is at times diverted into artificial channels and the whole of the gravel excavated from the bed of the river.

Workings in the solid rock are exceptional, save in a few special cases. Pegmatite veins are extensively worked by the ordinary methods of quarrying for felspar, quartz, and mica, but only occasionally have they been specially worked for gem-stones. Gem tourmaline has been so obtained in California and Maine, the crystals being broken out of cavities in the pegmatite; but the work is only on a small scale and soon abandoned. Pegmatites have also been worked in situ for tourmaline and beryl in Brazil and South-West Africa. At some places these pegmatites are weathered to a soft material which can be more easily worked. The sapphire-bearing pegmatite of Kashmir is, for example, weathered to a clayey material, and the pegmatites in Madagascar are altered to laterite to considerable depths. The emerald mines in Colombia are large open quarries in limestone on a steep hillside. The opal-bearing layers in sandstone in Australia are worked in a series of small open pits.

The only really extensive mining operations are those in the diamond mines in South Africa. The Premier mine near Pretoria is still worked as an open quarry, and the enormous pit is by far the biggest man-made hole on earth. The Kimberley mines, with a smaller surface area, were worked as open quarries down to a depth of 1300 feet, until this method of working became impracticable (Plate III). Work was then carried on by the ordinary methods of underground mining (fig. 41, p. 124), as in coal-mining and in metalliferous mines. These are the only underground

mines that are worked for precious stones. The whole mass of the rock is brought to the surface, and is crushed, washed, jigged, and dealt with just like an ordinary ore. The "blue ground" may, in fact, be regarded as diamond ore. Further particulars of the South African mines will be given in the chapter dealing with diamond (p. 123).

In the diamond fields of South-West Africa, conditions are quite different. Here the diamonds are found in the sand-dunes along the coastal strip of the Namib Desert. The content of diamond averages only one-fifth of a carat per cubic metre of sand and fine gravel, so large quantities of material have to be dealt with. The dunes are attacked with enormous mechanical excavators mounted on caterpillar trucks and driven electrically. At each scoop they pick up five tons of the loose material. One goliath that I saw there in 1929 was said to take up nine tons in one shovelful. The loose sandy material is dumped into trucks and conveyed by railways to the separating plants at Elizabeth Bay and formerly also at Kolmanskop, which can deal with 10,000 tons a day. Here it is sieved and washed in pans and pulsator jigs, and from the final concentrate the small diamonds are picked out one by one with a pair of tweezers.

CHAPTER IX

Cutting and Polishing Gems: Forms of Cutting

TO a crystallographer a clear and sharply developed crystal bounded by brilliant natural faces is of much more interest than one that has been cut and provided with artificial facets. In the latter state it shows no more than a sparkling bit of cut glass. The whole thing has an air of artificiality and is therefore to a student of nature objectionable. Whenever possible he strives to rescue a specially interesting or unique crystal from this mutilation; but owing to the high value of the material for gem purposes this is not always successful. However, the material produced by the gem miner usually consists of water-worn and damaged crystals with bruised edges and roughened faces, or of well-rounded pebbles. Such material may be readily sacrificed to the art of the lapidary. Indeed, it is often quite unattractive in appearance, and the ordinary person would not suspect it to be of any value. The colour, lustre, and brilliancy of the stone are brought out only when such material is cut and polished.

With transparent stones, either colourless or coloured, the object of the cutting is to produce a gem that will allow light falling on it to pass into the stone and then be reflected back to the observer. This is effected by cutting a number of small polished facets in certain directions on all sides. The optical properties (Chapter V) of the stone are then brought out to the

best advantage. On the other hand, with opaque stones and those showing special surface effects, as opal, moon-stone, cat's-eye, &c., only the surface presented to the observer is polished, usually with a rounded convex form.

The brilliant form of cutting is the one usually adopted for diamond and other colourless stones, but is also sometimes used with coloured stones. The ground-form of this is a truncated octahedron (fig. 28), with a large upper facet and a smaller lower one, both

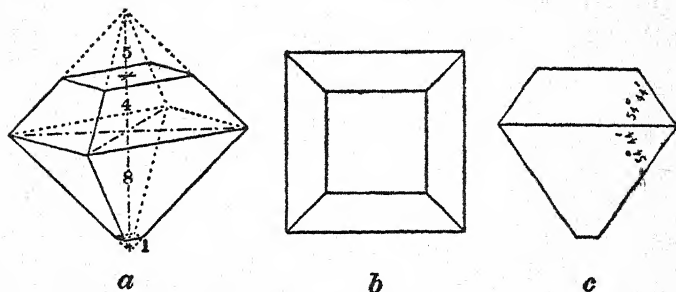


Fig. 28.—Octahedron as the ground-form of the brilliant-cut
(a) Truncated octahedron. (b) Plan of same. (c) Side elevation

parallel to a cube face of the diamond crystal. This quite simple form is the old "table-cut", and from it the brilliant-cut was evolved, additional facets being added symmetrically to give a "double-cut", and later a "triple-cut" brilliant. Fig. 29 shows the old form of the triple-cut brilliant, with thirty-three facets on the upper portion or crown, and twenty-five facets on the lower portion or pavilion. The edge between these two portions is called the girdle, and along this the gem is held in its setting. A comparison of figs. 28 and 29 will show that the four larger bezel facets of the crown, and the four larger pavilion facets below, correspond in position with the faces of the octahedron. It is to be noted, however, that the angle of slope of the faces is not the same in the two cases. The angle of slope

of $54^{\circ} 44'$ of the natural octahedron faces is too steep to give the best results according to the law of internal total reflection (compare figs. 18 and 19, pp. 44-5). From the critical angle of $24\frac{1}{2}^{\circ}$ in diamond it is possible to calculate the angles at which the facets should be placed to give the maximum result. In the drawing (fig. 29 c) the bezel facets are sloped at 36° and the pavilion facets at 41° . These exact angles apply of course only to diamond; with stones of other refractive indices and

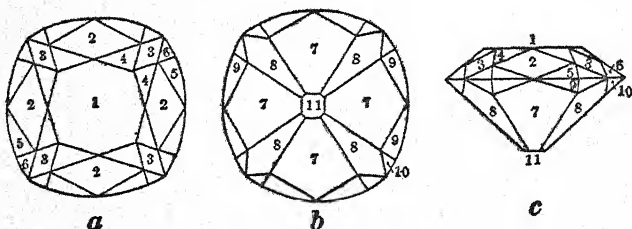


Fig. 29.—Brilliant-cut

(a) Upper side or crown. (b) Lower side or pavilion. (c) Side view.

In the Crown.—(1) Table. (2) Four templets or bezel facets. (3) Four quoins or lozenges. (4) Eight star facets. (5) Eight cross or skew facets. (6) Eight skill facets. Total 33 facets.

In the Pavilion.—(7) Four pavilion facets. (8) Four quoins. (9) Eight cross facets (10) Eight skill facets. (11) Culet. Total 25 facets.

critical angles they will be slightly different. This scientific principle has not always been appreciated by diamond cutters. The "Koh-i-Nur" diamond (fig. 43, p. 136) was cut too shallow, and the "Regent" (fig. 44) too deep. There should be a definite ratio between the "spread" or area and the thickness of a cut gem.

There are many modifications of the old brilliant-cut represented in fig. 29. More often the bezel and quoin facets in the crown are cut of equal size, and the pavilion and quoin facets below are also equal. The form then has a more circular outline. But this outline may also be modified in the efforts to produce bizarre shapes, or to produce the largest possible gem from the rough material available. In fig. 29 a beautiful fourfold

symmetry is displayed, just as in a tetragonal crystal. By the omission or addition of sets of facets, gems with a threefold or a sixfold symmetry may be cut.

Another form of cutting commonly adopted for diamond is the rose-cut (fig. 30), but only with small and flat stones. Here there is a single facet at the base of the gem from which the light is reflected. With coloured stones a common form is the step-cut or trap-cut (fig. 31), which has a series of parallel

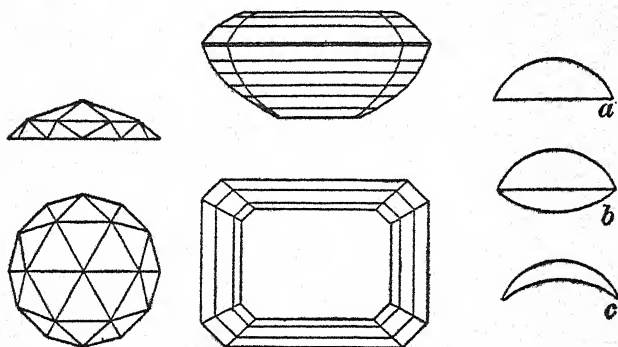


Fig. 30.—Rose-cut Fig. 31.—Step-cut or trap-cut Fig. 32.—Cabochon-cut
(a) Simple cabochon. (b) Double cabochon. (c) Hollow cabochon.

Various forms of cutting

strip-like facets increasing in steepness towards the girdle. The original star-cut consisted of a square or hexagonal table facet surrounded by four or six triangular facets, with rhomb-shaped facets in between and the girdle bordered by triangular facets; while the back of the stone was provided with a similar series of small triangular and rhomb-shaped facets. In later star-cut stones the number of triangular facets surrounding the table was increased until the star-like effect was obscured. Very large cut stones may show a profusion of hundreds of small triangular and rhomb-shaped facets (Plate VIII). In a "mixed-cut" the crown of the stone is brilliant-cut or star-cut while the back is step-cut.

These are the principal types of faceted cutting, but there is scope for endless variety; and the fashion in pendants and ear-ring drops must not remain stationary.

Opaque stones may be cut with a flat polished surface, as in seals and signet-rings. More often they are given a convex curved surface with a circular or oval outline. The degree of convexity varies with the kind of stone. A cat's-eye or star-corundum shows the chatoyant effect to better advantage when cut with a high dome-like form; while in an opal the play of colours is best seen on a flatter surface of slight convexity. These cabochon-cut stones (fig. 32) are usually given a flat base which is covered in the setting. The hollow cabochon (fig. 32 *c*) is usually used for red garnet (almandine and pyrope), and the stone is then often called a carbuncle.

The process of cutting is rather different with diamond than with other stones. As there is no harder material known, it is a case of diamond cut diamond; the process is tedious and slow, and consequently costly. Fortunately the octahedral cleavage of diamond affords a means of saving both time and material. A crystal can be cleaved into the more suitable ground-form; irregular and inferior quality portions can be removed; and large crystals can be divided. In the rather delicate operation of cleaving, a notch is first scratched with a diamond point in the required place and direction; a blunt knife is then placed in the notch and struck a smart blow. The cleaver must have some knowledge of crystallography, to be able to determine the correct orientation of the crystal. After cleaving (if this be necessary) the form of the gem is roughed out by a process of bruting. This consists in rubbing and scrubbing two diamonds together, to produce a round top-like form (fig. 33 *a*) with a flatter upper portion and a deeper lower portion. This tedious operation was formerly done by hand with the two diamonds cemented on the ends of short sticks. Now one diamond

is mounted on a lathe and the other used as the tool. All the abraded material is carefully collected for use in the next operation of grinding.

In this process of bruting, when a regular octahedron is being dealt with, there is a waste of much material in removing the large top corner (fig. 28 *a*), besides taking much time when done by hand. This top portion cannot be removed by cleavage, since diamond does not possess a cleavage parallel to the face of the cube. The new method is to saw it off, and the smaller piece can then be fashioned into another gem. This is done with a

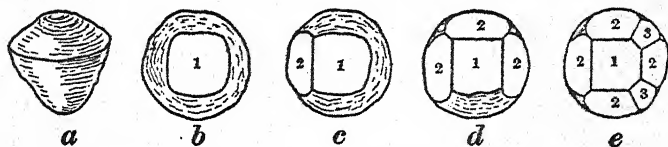


Fig. 33.—Stages in the cutting of diamond as a brilliant

(*a*) Bruted form. (*b-e*) Ground facets. (The numbering of the facets as in fig. 29.)

disk of phosphor-bronze, 6 cm. in diameter and $\frac{1}{16}$ mm. thick, charged on the edge with diamond powder and rotating at 4000 revolutions per minute. A larger crystal is sometimes sawn into two equal halves parallel to a cube face and is then ready for the bruting operation. A one-carat stone can be sawn through in about eight hours, but a larger crystal will take several days. However, the machines work automatically, and a whole battery of them does not require much attention.

The next operation is that of grinding the principal facets at the correct angles with the aid of a gauge. This is done on a lap or skeif, which is a wheel of cast iron revolving on a vertical axis at about 2500 revolutions a minute. Diamond dust mixed with oil is used as the abrading agent. The stone is firmly held by being embedded in an easily fusible solder alloy, from which it must be removed and reset for the grinding of each facet. A later form of holder or "dop" is a

screw clamp which allows several facets to be ground for each setting. The table facet is first ground (fig. 33 *b*), then the four bezel facets (fig. 33 *c*, *d*), and then the four quoins (fig. 33 *e*). This process is repeated with the nine principal facets on the lower portion, giving in all a total of eighteen. The stone then passes from the lapper to the brillianteerer, who grinds the remaining forty facets, judging their portion merely by eye. The weight of the dop keeps the stone pressed against the revolving wheel; and two or three dops may be left on the same wheel for the grinding to proceed slowly. The slow grinding produces at the same time the polish on the facets.

Compared with diamond cutting, the process of cutting other precious stones is much simpler. Their degree of hardness is very much less (see p. 118), and more effective grinding materials are now available. The rough stones may first be divided to a suitable size with a slitting disk, consisting of tinned iron charged with diamond powder at the edge. The stone is cemented at the end of a lapidary's stick (much like a penholder) and is held by hand against the surface of a rapidly revolving metal disk, or lap, charged with diamond powder, carborundum, or emery, mixed with oil or water. The angles of inclination of the several facets are regulated by inserting the top end of the stick in a series of notches in a "jamb peg" fixed to the working bench. After the several facets have been finely ground, they are polished on another lap covered with canvas or felt and charged with rotten-stone, putty powder, or rouge. Different kinds of stones need rather different treatment, with laps of harder or softer metal, and with different polishing materials.

Much of the work is now done on carborundum wheels. In the Idar district in Germany agate and other quartz varieties are cut on large sandstone wheels, five feet in diameter and eighteen inches thick, worked by water-power in a number of small establish-

ments on the banks of streams. The cutter lies face downwards in front of the grindstone and presses the stone to be cut against the edge of the wheel. Quartz (rock-crystal, citrine, and amethyst) and other softer stones are very successfully faceted by this method, the stone being held merely by hand; and the final polishing is done on revolving wooden cylinders. Faceted semi-precious stones are so produced in vast quantities, mainly from material of Brazilian origin, to be sold all the world over by "seaside lapidaries" as pebbles from the local beach. The trick is to encourage visitors to collect pretty (when wet) pebbles from the beach and leave them to be polished. After a suitable interval of time one of these German cut stones is produced, the original "valuable" pebble having in the meantime been consigned to the rubbish heap.

Seaside visitors who collect pebbles from the beach frequently ask how these can be polished. This is an operation that can be performed by the amateur, but it requires a certain amount of gear and a large amount of patience and time, and until the knack is acquired there will be many failures. Cabochon-cuts should be first tried before attempting any simple faceted forms. The stone may be first shaped on a carborundum wheel wetted with water. It is then ground with emery powder on a metal plate, or better, on a lapidary's lap running at a high speed from a small electric motor. The emery is mixed into a paste with water or oil, and in successive operations finer grades of emery are used. Care must be taken between each operation that both the stone and the lap are perfectly cleaned, otherwise a stray grain of the coarser powder will produce scratches on the more finely ground surface. When a perfectly smooth surface has been prepared the stone will be ready for polishing. This is done on a wooden disk with pumice powder or rotten-stone, and finished on a felt-covered lap with putty powder or magnesia.

CHAPTER X

Imitation Gems and Artificial Gem-stones

ON account of the rarity and costliness of precious stones, efforts have always been made to produce imitations and counterfeits in other materials by artificial means. Even the ancient Egyptians were experts in these matters. Some of their scarabs were cut in genuine turquoise and lapis-lazuli, but many more were made of a blue pottery or faience, or of glazed steatite. Coloured glass imitations were extensively used by the Romans. At the present day glass imitations are produced in vast numbers. The town of Jablonec (= Gablonz) in northern Bohemia is the centre of this industry, in which over 12,000 persons are engaged in the manufacture of glass beads and imitation gems. Many of the results are really quite pretty and effective, and they are displayed on the theatrical stage without a blush—but here the whole show is a pretence.

The glass used for this purpose is called "paste" or "strass", and is made of different compositions, but always with silica as a base. The best qualities are identical with optical "flint" glass, so called because crushed flint was originally used in its manufacture. The silica is now supplied in the form of quartz or a high-grade quartz sand (glass sand); but the material giving the special qualities is lead oxide, and this glass would be more appropriately called a lead glass. Such

a glass is prepared by fusing in a crucible in a glass furnace a mixture of sand (38-59%), red lead (28-53%), and potassium carbonate (8-14%) together with a little borax, white arsenic, and saltpetre. A glass of this composition has a refractive index of about 1.65, dispersion 0.03, and specific gravity 3.6. With more lead, up to 70% of lead oxide, a still denser, but very soft, glass with refractive index 1.8-1.9, and a dispersion equal to that of diamond, can be obtained. It is glass of this kind that is used in the construction of the refractometer (p. 58). Such glasses are very brilliant, and when cast in moulds or cut in the brilliant form they are sold as imitation diamond ("Parisian diamonds", &c.). By the addition of suitable metallic oxides in small amounts, imitation gems of any desired colour are produced.

There is one important point in which all these glass imitations fail, that is in the hardness. The more lead the glass contains, the more brilliant it is, but at the same time it is softer. The result is that these imitations, unless very carefully handled, become dulled by scratches, and their edges are easily abraded. In the operation of mounting they are often chipped at the edge of the girdle, and a magnifying lens will usually show the bright conchoidal fracture of glass. A further examination with a lens will also very frequently show the presence of minute round bubbles in the glass. Under the polarizing microscope they are optical isotropic and not pleochroic. But the quickest test of all is with a knife point: some can be cut almost like very hard cheese.

In former days this difficulty presented by the low degree of hardness was overcome by facing the fraudulent gem with a harder natural stone of poor quality, as in the so-called "doublets". The upper surface then resisted wear, while the softer material giving the colour was protected in the setting. Many very ingenious deceptions were formerly practised with these

doublets and even triplets. But now, with the production on a large scale of artificial gems consisting of the real material, there is no need for this. In antique jewellery the colour and lustre of a gem was usually "improved" by mounting it on a foil in a closed setting.

Natural stones are often coloured by artificial means. The process of staining agate is said to have been known to the Romans, and at the present day it is difficult enough to buy an agate that has not been so treated. "Swiss lapis" or "German lapis", now extensively passed off as lapis-lazuli, is a pale-coloured jasper or hornstone stained blue with ferrocyanide. Various colour changes can be produced in topaz, beryl, quartz, zircon and other gem-stones by subjecting them to a heat treatment. Brown zircon becomes colourless and very brilliant, and has then been sold as "Matura diamond". Amethyst becomes yellow and is passed off as topaz. Pale green beryl will sometimes give a rich sapphire-blue when the stone is heated; and yellow topaz becomes a beautiful rosy red, and has no doubt then masqueraded as ruby. Some gem dealers are really naughty people!

It is difficult to decide how far one is justified in "doctoring" a stone. In any case a natural stone has to be cut and polished before it is of any use as a gem. If at the same time the colour can be improved without altering the nature of the stone, then no harm is done, unless it is fraudulently passed off as something else.

Imitation gems made of materials different from those of the real stones are of necessity artificial or manufactured. But it is also possible to produce the actual stones themselves by artificial means. Most of the minerals known to occur in nature have, in fact, been produced in the laboratory, but, as a rule, only as quite small crystals or only of microscopic size. The crystals are in every way identical with those of the natural minerals, the same in chemical com-

position, crystalline form, and in their optical and other physical characters. They differ only in their mode of origin. The size to which they are grown depends of course on the element of time. Such products are known as artificial or synthetic minerals.

Unfortunately, in this connexion, the word "artificial" is liable to be misunderstood. All that is artificial in the process is in bringing together the proper constituents under conditions of temperature, pressure, humidity, &c., favourable for the growth of crystals. Nature then does the rest, and in exactly the same way that crystals of natural minerals have grown. The operations of the chemist are strictly analogous to those of a gardener, but nobody would suggest that products of the latter are "artificial" cabbages or roses. They may be cultivated, like "cultured" pearls and gentlemen. Adjectives are apt to get a little mixed when applied to different nouns. We may talk of wild roses and tame rabbits, but not of wild rubies and tame rubies; of artificial rubies, but not of artificial babies. "Artificial" flowers and eyes are made artificially, but they are neither flowers nor eyes. But rubies produced by the intervention of man are real, just as much as are babies. Like Topsy they have just grewed. Even Topsy must have had a father to initiate the process.

Neither is the adjective "synthetic" quite a happy one in this connexion. The artificial production of ruby is not one of synthesis by the combination of aluminium and oxygen. The material used is alum, and the process is rather one of breaking down, or analysis. Synthetic rubies are often mentioned, but never analytic rubies. Although gold is produced artificially from gold ore, we do not talk of synthetic gold or artificial gold. Mineralogists, however, distinguish "native gold"; and in this sense we may speak of native ruby. Then the "artificial" products could be called just gold or ruby. They could even be called

natural rubies, for they have actually grown according to the laws of nature. It is not yet possible to take the individual atoms of aluminium and oxygen and stick them into their proper places in the crystal-structure (fig. 3) and so produce a ruby artificially, in much the same way as the parts of an artificial watch or synthetic motor-car are assembled.

Many attempts have been made to produce diamond by artificial means. Minute crystals are said to have been obtained by some processes, but this requires confirmation (p. 138). Other gem minerals have been prepared as minute crystals, but it is only with corundum and spinel that material suitable for use as gems has been produced. Microscopic rubies were first made by M. A. Gaudin in 1837; and in 1877 beautiful crystals with the form of thin six-sided plates, from which a few minute gems were cut, were produced by Frémy and Fiel. In 1902, another French chemist, A. Verneuil, by an entirely new and unexpected process, was able to control the growth of large crystals of gem quality and of various colours. His apparatus (fig. 34) consists of an inverted oxyhydrogen blowpipe, oxygen being admitted at *O* and an excess of hydrogen at *H*. Inside the inner oxygen tube is a sieve *S* containing finely powdered alumina (prepared from alum), which is slowly fed by a tapping hammer actuated by an electromagnet *M*. The nozzle of the blowpipe is enclosed in a furnace box *B* containing a fireclay support carried on an adjustable stand *C*. The fine particles of alumina passing through the flame at a temperature of about 2000° C. are fused and fall on the fireclay support, and as this is gradually lowered a pear-shaped mass ("boule") is built up by accretion. The rate of growth is about 12 carats per hour and "boules" up to 250 carats in weight may be obtained. These pear-shaped drops have smooth glassy sides, usually round, but occasionally showing a rough hexagonal outline, while the flatter upper surface shows

a crystalline reticulation of minute triangles. In such a process one would expect to find the product to be an alumina glass or at least an irregular aggregate of minute crystals. But the really surprising result is that each "boule" is a single individual crystal possessing all the characters of a crystal of corundum. When the machine is fed with pure alumina the resulting crystal is clear and colourless; but with the addition of various metallic oxides clear crystals of any desired colour can be produced. By the addition of magnesia, crystals of spinel can be obtained by the same process. Verneuil generously gave to the world the results of his research work extending over many years in a series of papers published by the Paris Academy of Sciences. The process with some modifications and improvements is now worked on a commercial scale in France, Germany, Switzerland, and Italy, and the output of gem material of fine quality can amount to as much as a ton a day.

The result is that these artificially produced stones are much too common to command a high price. Coming into trade competition with the rarer native stones, they have been regarded with suspicion, and many are the attempts made to oust them and bring them into disrepute. The pretence that these artificial products are not real can only be harboured for selfish reasons. If Verneuil had kept the process a secret and placed the gem-stones on the market in strictly limited quantities, they would without doubt have been highly prized, and his truly remarkable scientific discovery

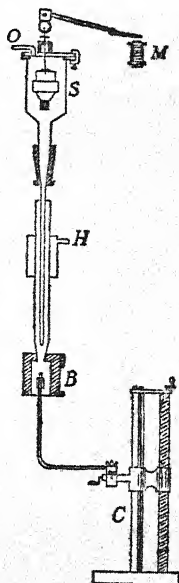


Fig. 34. — Verneuil's oxyhydrogen blowpipe for the artificial production of corundum.

would have been more fully appreciated. His generous action was surely a case of casting pearls before swine.

We do not find the same ridiculous outcry against some other minerals that are produced by manufacturing processes on a commercial scale. For example, epsomite or Epsom-salt was originally obtained in 1675 from the bitter spring at Epsom in Surrey, where at one time there was a fashionable spa. The native mineral, being readily soluble in water, is found only sparingly in a few places (just as are rubies), usually as a fibrous efflorescence on the walls of caves and old mine workings. In the latter case the formation of the mineral is indirectly due to the intervention of man, and the question arises how far is this an artificial mineral. The fastidious connoisseur who insists on having the native mineral, his epsomite from Epsom and his rubies from Burma, has of course to pay exorbitant prices, but he will find the manufactured products much purer and just as efficacious. He would surely prefer an artificial or cultivated cabbage to a native or wild cabbage.

Corundum is also produced on a large scale by fusing bauxite in the electric furnace at Niagara Falls. The crystallized product is crushed and sold as an abrasive in the form of powder, coated paper, and wheels under the names alundum, aloxite, and adamite. No objections are raised by lapidaries against this material on the grounds that it is artificial.

CHAPTER XI

Nomenclature of Gems: Names of Gem-stones and Minerals

THE names applied to gem-stones are often confusing and indeed deliberately misleading. It is well known that through the ages names have gradually changed in their meaning. A striking example of this is the name alcohol, which was originally applied to a mineral (see p. 197). The name sapphire was originally applied to lapis-lazuli, while our sapphire (blue corundum) was the hyacinthos (hyacinthus) of the Greeks and Romans, the name hyacinth being now applied to zircon. Carbunculus of the Romans included ruby and other fiery red stones, but this name is now restricted to garnet. Topaz or topazion and chrysolite have each had many favourites and have even changed places. In the olden days, when colour was the only criterion and hardness the only available test, stones were named only according to their colour; but, as we have already seen, this is a very variable and unreliable character. Even at the present time popular names are based merely on colour; and to meet the popular fancy many such names have been given deliberately for the purpose of deception. Such a term as "Brazilian sapphire" has been applied to both blue topaz and blue tourmaline from Brazil; and "Brazilian emerald" to green tourmaline, although true emerald has more recently been found in Brazil. "Siberian ruby" is tourmaline, and "Cape ruby" is

garnet; while "Brazilian ruby" is either topaz or tourmaline. "Spanish topaz", "Scotch topaz", and "occidental topaz" are quartz, and "oriental topaz" is corundum; while, strange to say, "Siberian topaz" really is topaz. We can only conclude from such a set of names that the jeweller's conception of gems is limited to sapphire, ruby, emerald, and topaz.

When we come to corundum we find a long array of borrowed plumes. The prefix "oriental" is added to the more familiar names emerald, topaz, chrysolite, amethyst, aquamarine, and hyacinth, with the idea of distinguishing different colour varieties of corundum. These are also duplicated in a parallel series of names in which sapphire has to play the part of the villain through the whole number, "green sapphire" being identical with "oriental emerald", "yellow sapphire" with "oriental topaz", &c. Another alias of yellow corundum is "topaz-sapphire". None of the minerals here named (except sapphire) has any connexion with the mineral corundum; and very often they are not of the colour they are supposed to represent. While poor sapphire is robbed of its own true blue, even to the extent of becoming "white sapphire".

The names "spinel-ruby" and "ruby-spinel", both of which are applied to red or ruby-red spinel, suggest that this system of naming gem-stones by false analogy is quite illogical. It leads to endless confusion and misunderstanding, usually to the advantage of the dealer, but also adding unnecessarily to the mystery of gem-stones. Those who still adhere to this antiquated system are recommended to wear an amethyst, which by its charm giveth good understanding to all things that may be misunderstood.

Why all this absurd nonsense—relics of the Dark Ages? Diamond shows just the same range of colours, yet it is always called simply diamond, and there can be no ambiguity or deception when one says red diamond. A dealer is never ashamed to sell a red

diamond or a blue diamond if it really is a genuine diamond; but he would rather pass off a yellow corundum under the more fanciful names "oriental topaz" or "yellow sapphire". But when artificial corundums are sold under the names "synthetic emerald", "synthetic alexandrite", &c., then it is a case of pure fraud.

The old names ruby and sapphire, emerald and aquamarine, and amethyst are all quite simple; and at the present time they have in all countries the same definite meaning. From them we have such well-known terms as ruby-red, sapphire-blue, emerald-green and amethystine. These are essentially gem names, but they are also in common use by mineralogists for colour varieties of the species corundum, beryl, and quartz respectively. Each of these mineral species is distinguished and defined by its chemical composition, crystalline form, and optical and other physical characters. Each one is a definite kind of material, and must be distinguished by a special name. Different specimens of the same kind of mineral may, however, differ very widely in their general appearance, and it is often convenient to have variety names in addition to the species name. To the mineralogist ruby and sapphire are both colour varieties of the species corundum, and emery is another variety.

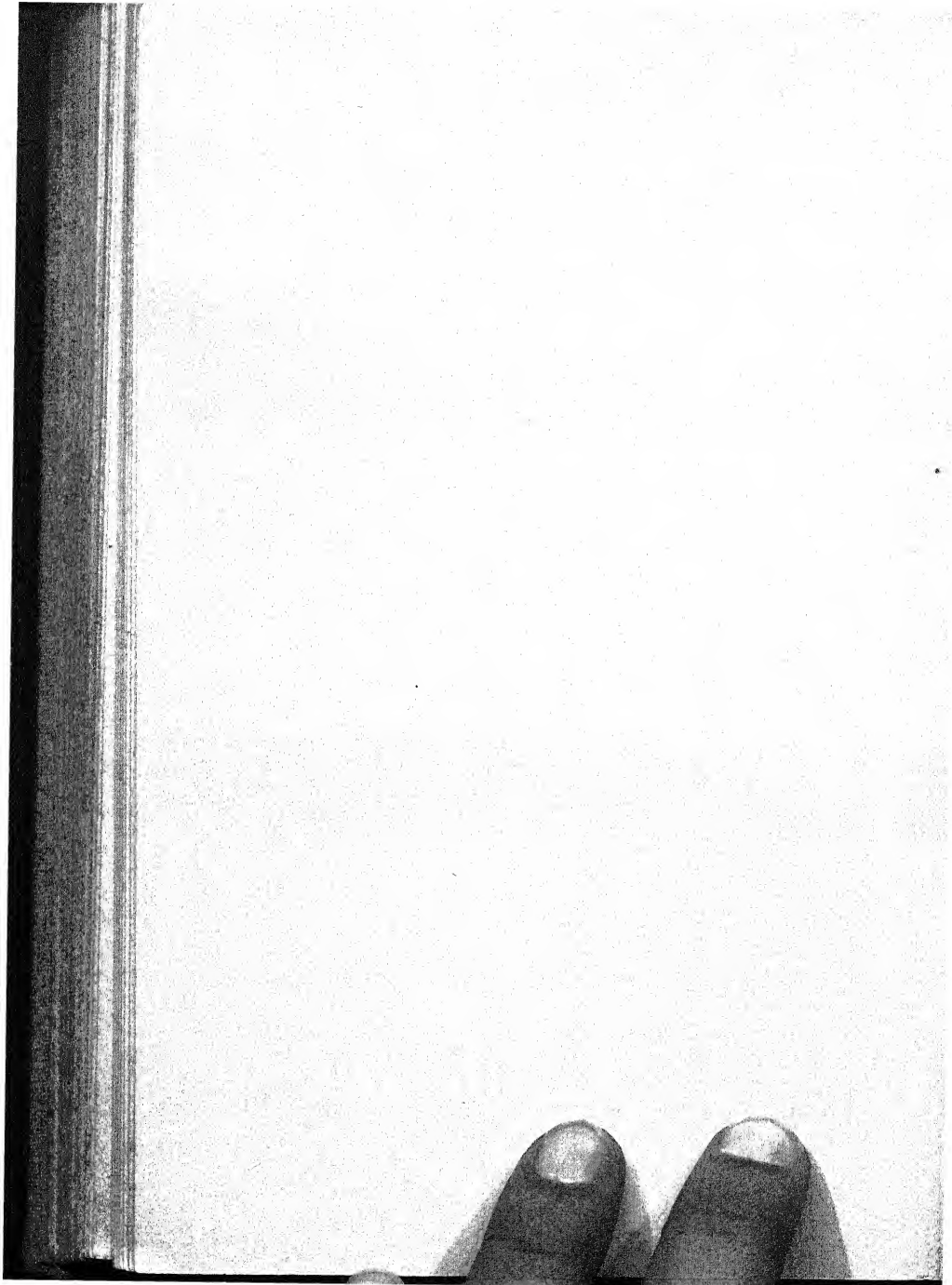
After all is said and done, gem-stones are merely minerals, and they are limited to only a few of the large number of known minerals. It is clearly unnecessary to have two different and opposed systems of nomenclature. For the complete and decisive determination of a gem-stone the methods of scientific mineralogy must be employed. If a particular gem of curious and unusual colour is examined and found to be corundum, then why not say so? Of course there is always a tendency and temptation to give a new name to a newly discovered variety; and a fancy trade name undoubtedly does help the sale of a thing. Any old

thing if well advertised under a new name can be made to go.

Every trade has its own special terminology. An egg merchant, for instance, does not say "eggs"; he talks of "Dutch brown", "Danish selected", "fresh farmyard", &c. A diamond merchant talks of "brilliants", "blue-whites", "pale bywaters", "macles", &c. There is a common parlance in every language and trade. Gem miners and local gem merchants have names of their own for the different varieties and qualities of stones. For example, in Ceylon, ruby is called "rata ratugal" or "ratukete", sapphire "nila", yellow corundum "pusparaga"; and salmon-pink corundum is called "king topaz", or in Sinhalese, "padmaragaya". The last name (from *padma*, lotus, and *raga*, colour) has been adopted in Germany in the incorrect forms "padparadschah" and "patparadscha" as a trade name for artificial corundum of a salmon-pink colour.

In this book the common and simple gem names will not be ignored, but they will be put into their proper places under the different mineral species. A list of mineral species which have supplied gem material has been given with the chemical composition of each at the end of the chemical chapter (p. 73). In the chapters which now follow descriptions will be given of each of these mineral species, in very much the same order as shown in the chemical classification. This happens to fall in more or less with a classification of gem-stones according to their rank of importance and rarity. Diamond as a chemical element heads the list. Then the oxide corundum, followed by the aluminates and silicates.

PART II
DESCRIPTIVE PORTION



CHAPTER XII

Diamond

DIAMOND is unique in its properties, not only amongst gem-stones, but also amongst minerals and all known materials. Yet it is composed merely of the common and abundant element carbon, consisting of the same chemical material as charcoal, soot, and graphite. Every man of eleven stone is carrying about with him twenty pounds of carbon—enough to make a far bigger diamond than ever recorded. Yet diamond is of very rare and sporadic occurrence as quite small crystals, and it has defied all attempts to produce it by artificial means.

The name diamond is a corruption of the Greek and Latin *adamas*, originally meaning “the invincible”, and afterwards applied to hard metals and stones. The old form of the name is used in the English translation *The Mirror of Stones* (London, 1750) of the *Speculum Lapidum* (Venetia, 1502) by Camillus Leonardus:

Adamant, or the Diamond, is a most precious Stone, of the Colour of polish'd Iron, and as it were Christalline. Its Quantity is never found larger than the Bigness of a Filberd. It will give way to no Sort of Matter, neither to Fire nor Iron, but despises all; it had its Name from the *Greek* Interpretation, which is, *an unconquer'd Virtue*. Some hold, it can be mollified only by the warm Blood of a Goat; which is fabulous, since I have seen many broke with the Blow of a Hammer. Neither is there any Thing so hard, but it will suffer by the *Adamant*. . . . Its Virtue is to repel Poison, tho' ever so deadly; is a Defence against the Arts of Sorcery; disperses vain Fears; enables to quell all Quarrels and Contentions; is a Help to

Lunaticks, and such as are possess'd with the Devil; being bound to the left Arm, it gives Victory over Enemies; it tames wild Beasts; it helps those who are troubled with Phantasms, and the Night-mare; and makes him that wears it bold and daring in his Transactions.

In the old days, when India was the only source of supply, diamond was exceedingly rare. It was known to the Romans, who used it as an engraving tool in the production of their wonderful cameos and intaglios in hard stones; but it was probably not used by them as a gem. The early process of diamond cutting, introduced from India into Europe in the fourteenth century, did little more than polish the natural crystal faces and replace irregular areas by a number of small facets. The first regular forms of cutting were done by Ludwig van Berquen at Bruges in 1476; whilst the brilliant form of cutting, most suitable for bringing out the optical characters of the stone, was not developed until the seventeenth century.

Diamond has always been a mysterious and puzzling stone, and it still presents many outstanding problems. Sir Isaac Newton had suggested that it was composed of some combustible substance; and in 1694 the Academicians at Firenze (Florence) showed that diamond was consumed when exposed to the sun's rays at the focus of a large burning-glass. A hundred years later it was proved that the product of combustion was the gas carbon dioxide, and that the same amount of this gas was produced by the burning of an equal weight of charcoal. Heated in oxygen to a temperature of 850° C., diamond burns with a small blue flame. At a much higher temperature in the absence of air it is converted into graphite. Diamond therefore consists of pure carbon, and it is the only gem-stone that is composed of a single chemical element.

Graphite also consists of pure carbon. A more striking difference than that between the two can scarcely be imagined. Diamond is the hardest of all minerals and

graphite the softest; one is used as a cutting and abrasive agent, and the other as a lubricant. Diamond is brittle, and possesses a high degree of elasticity, whilst graphite is flexible and inelastic. One is colourless and transparent and a bad conductor of electricity; whilst the other is black and opaque and a good conductor. There is also a wide difference in the density, diamond 3.52, graphite 2.25. Diamond crystallizes in the cubic system and breaks along four perfect cleavages parallel to the faces of the octahedron. Graphite crystals have the form of six-sided scales with one perfect cleavage parallel to the large surface of the scales. Why these marked differences between materials that are chemically identical? They evidently bear some relation to the way in which the atoms of carbon are arranged to build up the crystal structure. After all the study of crystals (crystallography) is really of interest, if not of some importance. Now we can get on with the crystallography of diamond, but under restraint, as there are many other matters to be considered.

The most usual form of diamond crystals is that of the octahedron, but only rarely do we see a regular and sharply developed form as in fig. 4 (p. 32). Usually the edges are rounded (fig. 35) or marked with V-shaped grooves (fig. 39). The faces also are often rounded, and the form grades into that of the rhombic-dodecahedron, a tetrakis-hexahedron (four-faced cube) (fig. 36), or a hexakis-octahedron (six-faced octahedron) (fig. 37). These rounded forms are especially characteristic of diamond, and are not found in any other mineral. Often also, a crystal is flattened or elongated in one direction due to irregularities of growth; and it is sometimes difficult to decipher the form. Flat faces of the octahedron are usually marked by platy growths and by minute triangular pits (fig. 35), which, viewed with a magnifying glass, are very delicate and beautiful. On the cube faces similar pits are square in outline.

Diamond is usually found as isolated single crystals bounded on all sides by faces. They did not grow attached to a matrix, like crystals of quartz, beryl, topaz, &c. An intergrowth of two crystals is, however, not uncommon, but the intergrowth is often so intimate that it is not always easy to detect. These are known as twins or twinned crystals. One type of twin may be illustrated by cutting a model of an octahedron into two equal halves parallel to one pair of faces and turning one half through 180° about an

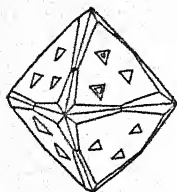


Fig. 35.—Octahedron with bevelled edges and pitted faces

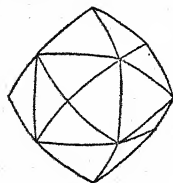


Fig. 36.—Tetrakis-hexahedron with curved faces.

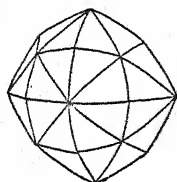


Fig. 37.—Hexakis-octahedron with curved faces.

Crystals of Diamond

axis perpendicular to the cut, when the two parts fit together again. This type of contact twin is specially characteristic of spinel and is known as the spinel twin (fig. 38). Here there is a change in direction of the cleavage across the plane of twinning, which is a point of importance to the diamond cutter. In diamond these twins are usually much flattened parallel to the plane of twinning, and they often have the form of thin triangular plates. An interpenetration twin of two tetrahedra with the corners truncated gives an octahedron with grooved edges (fig. 39). This raises the question whether diamond has the full symmetry of the cubic system, or only tetrahedral symmetry, a point which has long been discussed. X-ray analysis shows that some of the atoms are placed in tetrahedral positions with respect to others. Fig. 40 shows atoms at the eight corners of the main cube with one at the centre

of each face; this is the face-centred cube. Midway on the diagonals (marked by dotted lines) of alternating sub-cubes four atoms (marked as double circles) are placed inside the cube. With two kinds of atoms, as indicated in the diagram for clearness, this represents the structure of zinc-blende (zinc sulphide), the unit cube containing four atoms of zinc and four of sulphur. If all the atoms are of the same kind, the structure is that of diamond, the unit cell containing eight carbon

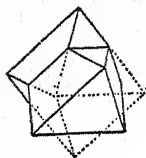


Fig. 38.—Twinned octahedron ("spinel twin").

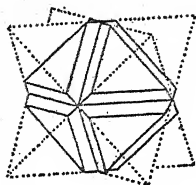


Fig. 39.—Twinned octahedron (interpenetrating tetrahedra).

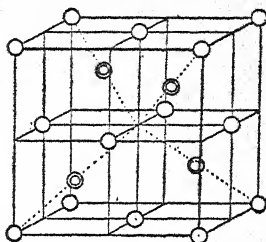


Fig. 40.—Structure model

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atoms. A bright boy will count eighteen atoms in the picture; but each one at the corners is shared by eight adjacent cubes meeting in the corner, making eight-eighths, or one, for this particular cube; and those in the centre of each face are shared by two adjacent cubes, making three in all; with the four atoms inside the cube, this gives a total of eight. This unit cube has an edge of 3.56 Ångström units (3.56×10^{-8} cm.), and adjacent atoms are at distances of 3.56, 2.52, and 1.54 Å. apart. It will be seen from the diagram that the double-ringed circles in the centre of the sub-cubes are equidistant from four single-ringed circles, i.e. at the centre of a tetrahedron with these four at the corners (cf. fig. 11, p. 35). When the structure is extended by repetition, it will be seen that each single-

ringed circle is also equidistant from four double-ringed circles.

In size diamond crystals are always quite small. An octahedron weighing one carat measures about a quarter of an inch across, and this is well over the average size. The largest crystal ever found was the "Cullinan" diamond, which measured $4 \times 2\frac{1}{2} \times 2$ inches, and weighed 621.2 grams = 3106 carats = $1\frac{1}{8}$ lb., but this was quite exceptional. Other crystals may be $\frac{1}{2}$ millimetre down to microscopic dimensions. The average size of British Guiana diamonds is six to the carat. Sizes are of course relative. If these amounts were expressed in Ångström units, long rows of figures would be shown. Compared with crystals of some other gem minerals, these sizes are insignificant. Beryl crystals have been found in Maine, U.S.A., up to 18 feet long and weighing 18 tons (Plate VII), and the record for a crystal of topaz is 500 lb.; but these are not of gem quality. Felspar crystals in Norwegian felspar quarries are said to weigh up to 200 tons. If diamond were found on this scale it could be put to many useful purposes, but it would then be too common to be valued as a gem.

The crystals as found are often quite clear and transparent with a brilliant lustre on the surface. The special type of lustre characteristic of diamond is known as adamantine lustre. When the surface is dull and rough the lustre often has a sub-metallic appearance, some opaque crystals looking almost like metallic lead. The full brilliancy, fire, and play of prismatic colours for which the diamond is so much admired as a gem are only brought out by the cutting and polishing. The form of cutting best suited for this purpose is the brilliant-cut (fig. 29), and for this reason diamonds are often referred to by the trade as "brilliants". Small flat stones can only be fashioned as the rose-cut (fig. 30).

A stone used for cutting as a gem must be a single homogeneous crystal. Other stones may, however,

consist of an irregular aggregate of crystals. These, together with badly coloured and flawed stones, are classed as *bort*. Such material has many practical uses because of its extreme hardness. It is the most efficient of abrasives, and is indeed the only material with which diamond itself can be ground and polished. It is used for cutting and drilling hard stones and rocks; as an engraving and cutting tool; and when pierced with a fine hole, for drawing fine wire, such as that used in electric-light bulbs. The glazier's diamond, undoubtedly the most used and useful of diamonds, is a small crystal or fragment with a cusped edge between two curved crystal faces. Spherical *bort* (shot *bort* or *ballas*) consists of a radial aggregation of fibrous crystals, and this kind is especially valuable for rock-drills. Another form of aggregation is seen in *carbonado* ("carbon" of the trade), which consists of a vast number of minute crystals compacted together as a dull black mass. (Marble consists of a similar aggregate of minute crystals of calcite.) This material is as hard, but tougher and less brittle than a single crystal of diamond, since it cannot be split along a cleavage. It is in great demand for rock-drills and commands a high price. Not very long ago it fetched a higher price per carat than did material of good gem quality. The steel crown of the drill studded with these stones is indeed a crown of jewels, and one that is of really practical use in drilling tunnels and deep shafts through hard rocks.

But to return to our gems. Apart from hardness and rarity, the special qualities of diamond depend on its optical characters. Combined with perfect transparency, it has very high refractive and dispersive powers. The refractive index is 2.402 for light at the red end of the spectrum (wave-length 7628 Ångström units), and 2.465 at the violet end (wave-length 3969 Å.). The difference, 0.063, between these two values gives a measure of the dispersion. The refractive index is

2·417 for yellow sodium-light, which is a convenient monochromatic light for use as a standard. Some minerals have a refractive index greater than that of diamond (one of these is rutile), whilst demantoid and sphene have higher dispersive powers. Corresponding to the high refractive index, the critical angle of internal total reflection is only $24\frac{1}{2}^{\circ}$ in diamond (as compared with about 40° in ordinary glass). More light is therefore reflected out from the back of the cut stone. The adamantine lustre and the brilliancy are also functions of the high refractive power. In consequence of its high dispersive power a properly cut diamond displays the well-known flashes of brilliant prismatic colours. Being a cubic crystal, diamond is normally optically isotropic, but some crystals, when examined under the polarizing microscope, show a feeble double refraction in patches, especially around enclosed foreign particles. This is due to a state of strain in the crystal; but stories of explosive crystals are mythical.

The purest diamonds are colourless and water-clear. Such stones are described as of the "first water" or "blue-whites". Many stones, especially those from South Africa, show a slight yellowish tinge, and when this is pronounced they are referred to as "off colour" stones. Apart from dirty grey and dingy brown, distinctly coloured diamonds are rare. They may be of any colour—red, pink, orange, yellow, green, blue, violet, brown, black. Examples of famous coloured diamonds are the "Hope Blue", "Dresden Green", and "Tiffany Yellow".

A few other characters remain to be mentioned. The high degree of hardness is not well expressed by No. 10 on Mohs's scale. As shown by grinding tests, diamond is 140 times harder than corundum (No. 9 on the scale), and more than a thousand times harder than quartz (No. 7). The degree of hardness differs on different faces of the crystal, being greatest on an

octahedron face and least on a cube face. On this account it is almost impossible to grind a facet strictly parallel to an octahedron face. Crystals are sawn parallel to a cube face, and whenever possible this is made the table facet. Also the hardness on each face varies with the direction (a vectorial property in crystals) and a good cutter grinds along the "grain".

The specific gravity of clear diamond shows only a small range, 3.50-3.52; but for the somewhat porous carbonado it is lower, 3.15-3.30. Some few diamonds show a luminosity in the dark after exposure to bright sunlight (phosphorescence) or when rubbed (triboluminescence). Some show a luminosity (fluorescence) when exposed to ultra-violet, cathode, or X-rays, or to the emanations from radium. Under the ultra-violet rays some colourless diamonds show a cornflower-blue glow, and some greenish diamonds a greenish-yellow glow. Exposure to ultra-violet rays produces an electric current through some diamonds (photoelectric effect). Diamond is much more transparent to Röntgen rays (X-rays) than other minerals, and much more so than glass imitations. After long exposure to radium a colourless diamond becomes green. Diamond is a good conductor of heat, and consequently it feels colder than glass; also a film of moisture from the breath will disappear more quickly off the surface of diamond than off glass.

The occurrences of diamond are very restricted. It has been found in only few places in widely scattered parts of the world. Further, it has been found only in secondary deposits and never in the place where it was originally formed. The original home of the diamond has yet to be discovered. This is disappointing from a scientific point of view, but perhaps fortunate for the trade, otherwise there might be a serious slump in prices. Mr. Alpheus F. Williams, for many years the general manager of the De Beers Consolidated Mines at Kimberley in South Africa, has recently

written two large volumes on *The Genesis of the Diamond* (London, 1932), but he leaves the problem unsolved.

In Europe a few crystals have been found in gold-washings in the Ural Mountains, and two small crystals are said to have been found in Bohemia. Until the discovery of the Brazilian deposits in 1725 and the still more important deposits in South Africa in 1867, the only sources were India and Borneo. Indian diamonds have been known since remote times; little information is available about the early finds in Borneo, but they were mentioned in the sixteenth century. The production in India now amounts to only a few hundred carats a year.

The fabulous mines of Golconda have often been mentioned in books with much glamour. This now ruined city, a few miles from Hyderabad, was really the trading centre for the diamonds found over a wide area in the gravels of the Kistna, Pennar, and Godavari rivers in Hyderabad and Madras in southern India. A northern group of workings was along and between the Ken and Son rivers in Bundelkhand; and an eastern group is in the Mahandi and Brahmani valleys in Bihar and Orissa. The workings were not only in the recent gravels in the beds and banks of the present-day rivers, but also in older high-level gravels deposited by earlier rivers. The diamonds in the recent gravels had been partly derived from the older gravels; and in turn these had been derived from still older rocks in which the gravel beds are now consolidated into conglomerates. These older rocks belong to the Vindhyan system of Indian geology and are supposed to be of pre-Cambrian age, a matter of about a thousand million years ago. The rocks of the Vindhyan system are sedimentary rocks formed by the breaking down of pre-existing rocks by the action of the weather and the deposition of the debris in water. Whence the Vindhyan rocks got their diamonds is not known. No trace has been found of the original deposits. The native

methods of mining have always been very primitive, and the deposits are too poor and scattered for any systematic mining on a large scale. In the hard conglomerate, resource was made to fire-setting, the rock face being heated with a brushwood fire and then quenched with water.

In Brazil the story is much the same. The diamonds have been found, often along with gold, in recent gravels in the basin of the Jequitinhonha in the State of Minas Geraes, and in that of the Paraguassú in the State of Bahia. They are also found in the older plateau gravels. These gravels have been derived from sedimentary rocks (conglomerates and sandstones) of the Itacolumy and Lavras series, which are here also of pre-Cambrian age. In certain softer portions of these old rocks diamonds have been found in a highly decomposed matrix, which some authors have compared with the kimberlite of South Africa, and believed to be the original matrix of the diamond, but the evidence is not conclusive. There is one important difference between the alluvial deposits of Brazil and those of India, and this may give a detective clue to solve the mystery of the origin of the diamond. In the Brazilian gravels diamond is found with various associates of strange character; and a wanted man can often be traced through his friends. These associated minerals, some of which are gem minerals, are indeed taken by the miners as indications of the presence of the precious stone. They are usually found as small bean-shaped pebbles called "favas", and include perovskite, anatase, rutile, chrysoberyl, tourmaline, kyanite, &c., and xenotime and other complex phosphate minerals. The pebbles found with Indian diamonds are only quartz and variously coloured jaspers. The compact black diamond, carbonado, is peculiar to Bahia.

In South Africa the story has been very different, although here the first diamonds were found in river gravels; but soon afterwards they were traced to a new

and unsuspected source. In the early days some geologists had doubted whether South Africa would yield many diamonds, since the geological conditions are different from those in India and Brazil. This is a warning that even geologists must be on their guard when dealing with diamonds. But they must also consider the possibility of "salting", which has been resorted to by some unscrupulous claim holders. In the year 1867 an intelligent pedlar noticed a curious stone amongst the pebbles which a Boer child had as playthings on a farm near Hopetown on the Orange river. This he showed round, finally meeting a good mineralogist, who spotted it as a diamond. This stone of $22\frac{1}{4}$ metric carats was shown at the Paris Exhibition of 1867, and it led to the first diamond rush in South Africa. The "river diggings" soon extended to the Vaal river, and in 1869 the "Star of South Africa" or "Dudley" diamond was found on the Orange river. This weighed in the rough $85\frac{3}{4}$ metric carats and yielded a cut stone of $47\frac{3}{4}$ metric carats. These rivers have often been diverted into temporary channels and the whole bed torn up in the intensive and feverish search for diamonds, when lucky finders quickly made fortunes, but for the majority it was a poor game. Later, in 1869-71, further discoveries were made in several shallow depressions or "pans" on the arid plateau between the Vaal and Modder rivers. This led to another diamond rush and the founding of the now important town of Kimberley. The workings here were distinguished as "dry diggings", and included the famous mines De Beers, Kimberley, Dutoitspan, and Bultfontein, and later the Wesselson mine and some others. About the same time similar deposits were found at Jagersfontein and Koffyfontein in the Orange Free State.

The deposits in which these "dry diggings" were worked soon proved to be of an entirely new type. Each occupied an approximately circular or oval area

about 200-300 yards across, and more diamonds were found in depth. Down and down the miners delved into the bowels of the earth after the precious stone, until open mining became quite impracticable. A more leisurely miner, working alone on his claim of thirty-one feet square, was soon left on the top of a high tower surrounded by his more energetic neighbours, who had subdivided their claims. There was trouble when the narrow roadways giving access to the several claims began to collapse, and when the sides of the main pit began to fall in. Each claim was then connected with the outer edge by wire ropeways, and the thousands of wires spread out like a gigantic cobweb over the yawning pit. Individual working became impossible, and amalgamation was necessary. Finally, in 1888, the master mind of Cecil Rhodes effected the amalgamation of the whole group of Kimberley mines as the De Beers Consolidated Mines. Plate IV represents a specimen from the old open workings of the De Beers mine at Kimberley, which was given by Rhodes to George Hudson, then Treasurer-General of Griqualand West, to commemorate this event, and which was presented in 1933 to the British Museum collection of minerals by the latter's son, Mr. W. T. Hudson.

The open workings had to be abandoned, but these now remain, some surrounded by houses, as impressive sights in the town of Kimberley. The funnel-shaped pit of the Kimberley mine (Plate III) measures 1500 feet across, with a depth of 1300 feet, but with water standing in the bottom. Vertical shafts were then sunk with great labour through the hard rocks surrounding the mines, and horizontal tunnels were driven from them to the diamond-bearing ground. This is excavated along galleries by the ordinary methods of mine stopping (fig. 41), and millions of tons of the material brought to the surface for further treatment. The underground workings in the Kimberley mine now extend to a depth of 3600 feet, and are still in the diamond-

bearing ground, which extends to an unknown depth.

The diamond-bearing ground is known to the miners as the "blue ground", and it forms the filling of enormous vertical pipes which penetrate the horizontally bedded rocks of the district. In the early workings, in the upper part of the pipes, it was called the "yellow

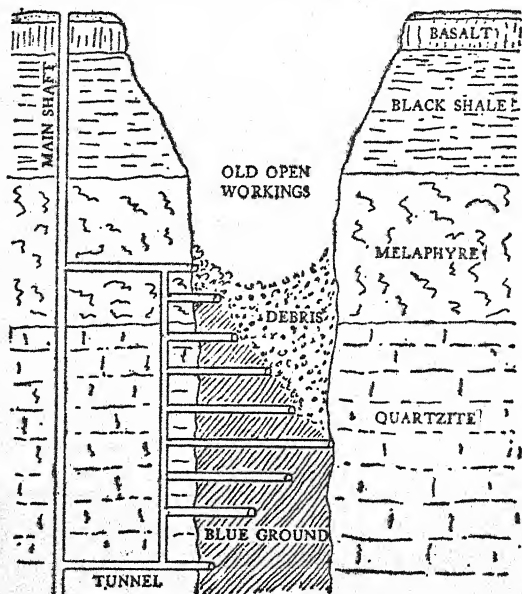
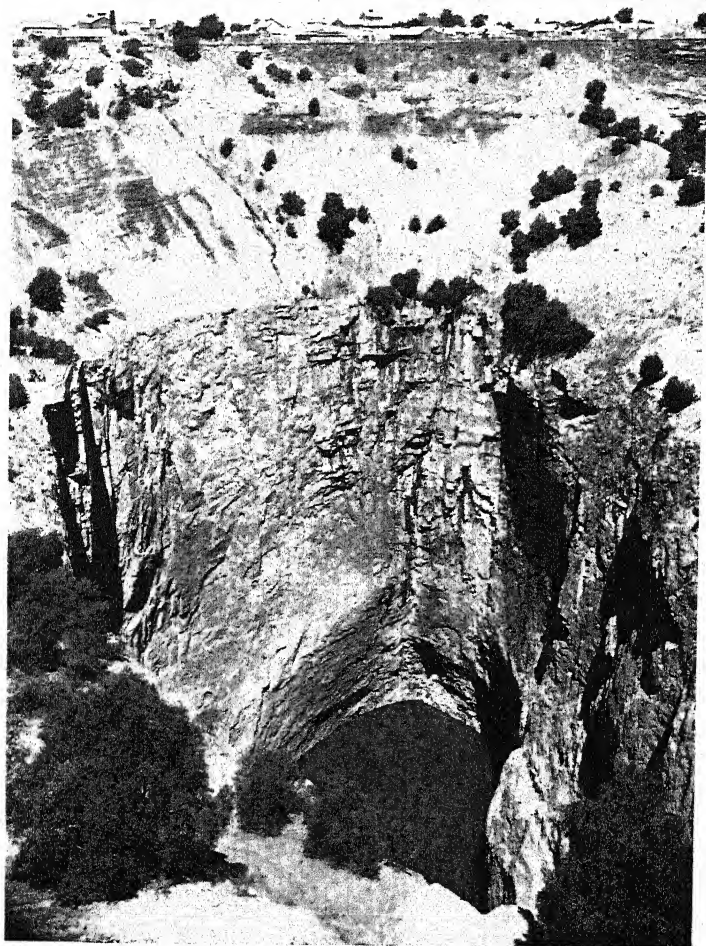


Fig. 41.—Diagrammatic section of a diamond mine at Kimberley, South Africa. Showing underground workings in a pipe of blue ground

ground", the change in colour being due to surface weathering and oxidation. This "blue ground" has been, and still is, the subject of much study. It is known to petrographers (rock experts) as kimberlite, being a rock of a special type and peculiar to the district after which it takes its name. It is described as an igneous rock of the peridotite family. This means that it should be composed mainly of the mineral olivine (or peridot), a silicate of magnesium. But



THE ABANDONED OPEN WORKINGS OF THE KIMBERLEY
DIAMOND MINE AT KIMBERLEY, SOUTH AFRICA

The pit measures 1500 feet across and 1300 feet in depth
(Depth to surface of water 930 feet)



here the olivine has been largely altered by hydration to a hydrated silicate of magnesium, and the rock has more of the character of a serpentine-rock. But it differs considerably from the usual type of serpentine-rocks. It is much broken and fragmentary, and contains embedded blocks of foreign rocks and odd fragments of various minerals. Some of these rocks in the form of irregular fragments have been torn away from the walls of the pipes. Others, such as granite, mica-schist, eclogite and garnet-rock, have the form of rounded boulders as if worn by violent attrition. Rocks of the latter kind are not known to outcrop in the district and they must have been brought up from great depths in the earth's crust. The mineral fragments include ilmenite, pyrope, zircon, enstatite, chrome-diopside, iron-pyrites and many others; and last but not least in importance, though least in amount, the diamond itself, which also is sometimes found as broken fragments. In the richest parts of the Kimberley mines diamond is present to the extent of one part in two millions of the blue ground, but the average is only one part in fourteen million (0.00008%); whilst there are hundreds of other blue ground pipes in South Africa that are almost or quite barren.

This is surely a strange place in which to find diamonds. Where have they come from? Here we have the materials for a really good detective story with plenty of mystery, sensation and tragedy. The main drama appears to have happened some sixty million years ago. The blue ground is really a volcanic agglomerate and the pipes are the necks of volcanoes. But these again were not of the ordinary type, not like the well-behaved Vesuvius on the slopes of which a large population can live in comparative safety. They were of the violently explosive type, bringing up and churning together a mixture of materials from the bowels of the earth. There is no evidence that these volcanoes erupted at the surface of the earth; and

it is clear that the tops of the pipes, together with the surrounding rocks, have been very considerably worn down by denudation since the eruptions took place in the Cretaceous epoch. These pipes at Kimberley, and also, no doubt, other undiscovered pipes, must be the source of the diamonds found in the neighbouring river valleys. But of the diamonds in the pipes we can only say that they came from some place deep down in the earth's crust. Diamond is evidently a mineral of igneous origin. If similar diamond-bearing pipes exist in India and Brazil, they would belong to a much earlier period of the earth's history, for these diamonds are found in conglomerates of pre-Cambrian age; and the chances are that the eroded tops of the pipes are now hidden under a rock cover.

The blue ground after being hauled from the mines undergoes a special treatment for separating the diamonds. These are present in such relatively small amount that only rarely is one to be seen actually embedded in its matrix. In the old method the rather hard rock was spread out on extensive floors for a year, where by exposure to the weather and frequent harrowing and rolling (quite an agricultural operation) it was broken down. These floors were surrounded by barbed-wire fences and carefully guarded day and night. The present method is to pass the rock through crushers and rolls provided with special springs to avoid breaking any large diamonds. The disintegrated material then passes to the large circular washing pans provided with rotating arms. All mud and lighter material are so washed away in a stream of water. The heavier concentrate, amounting to about 2%, so obtained then passes to pulsator jigs, where in water a further separation is made according to specific gravity, diamond, with a specific gravity of 3.52, remaining with the other heavy minerals (garnet, zircon, iron-pyrites, &c.). The final concentrate goes in a stream of water over vibrating tables coated with cart

grease. Diamond has the curious property of sticking to the grease, whilst the other minerals slide over. The average daily output of blue ground from each of the Kimberley mines is about 4000 tons.

Many (some 150) blue-ground pipes, similar to those at Kimberley, are found over a wide area in South Africa, a few extending also into South-West Africa, Southern Rhodesia, Belgian Congo, and Tanganyika Territory; but only a few of them have been proved to be productive. The most remarkable one is worked as the Premier mine, twenty miles north-east of Pretoria in Transvaal. It was discovered in 1903. Here the extra large pipe measures 2900 by 1400 feet across. It has been worked only as an open mine, the depth now reached being 640 feet. This surely is the biggest man-made hole on earth; and the waste dumps look like mountains from the distance when approaching the mine. Looking down into the enormous pit when the blasting charges are being fired is a most impressive sight. At the time of my visit in 1929 fifteen hundred shots were fired; there was a regular bombardment, and rock fragments flew high into the air, but none outside the deep pit. The most astonishing part of the performance was to see, after the last shot, thousands of black men rushing from cover like ants at the bottom of the pit. Those who filled their trucks first gained a small reward. Some idea of the amount of work that has been done at the Premier mine is given by the following total figures for the period 1903 to 1930: blue ground washed 129,910,427 loads, diamonds recovered 28,459,829 $\frac{3}{4}$ carats, valued at £32,392,829, 10s. 10d.

The production of diamonds for the whole of the Union of South Africa reached peak values in 1906-14 with over five million carats (one ton!) in each year, the larger part being from the mines. In 1927-29 similar values were again reached, following the discovery of the rich alluvial deposits in the Lichtenburg district in the Transvaal.

Many interesting yarns could be told of the conditions of life in the early days on the diamond fields, illicit diamond buying, the compounds for the native workers, &c., but before we leave South Africa there are still a few more points of mineralogical interest. Small green diamonds are occasionally found in the gold-bearing "banket" of the Witwatersrand, especially at Modderfontein on the eastern Rand. This rock is a conglomerate of pre-Cambrian age, so these diamonds are very much earlier than those in the blue-ground pipes of Cretaceous age. Where they can have come from is not known. The rich alluvial deposits discovered in 1926 in the Lichtenburg district in south-western Transvaal belong to the gravels of an ancient river system, and rich finds were made in large pot-holes in the underlying dolomite-rock. These, as well as the rich deposits found in 1927 along the coast at the mouth of the Orange river in Namaqualand, were no doubt derived from the blue-ground pipes. In South-West Africa large numbers of small diamonds have been found in the sand-dunes of the coastal desert.

Within recent years diamonds have been discovered in other parts of Africa. They have been found in considerable amount, but of poor average quality, near the borders of Belgian Congo and Portuguese Angola, and extending northwards into French Equatorial Africa. In West Africa a good many small crystals have been found in the Gold Coast; a few in Liberia and Sierra Leone; and in 1934 a single fine crystal of ten carats in Northern Nigeria. Other African localities are in Southern Rhodesia and Tanganyika Territory.

Diamonds have also been found in Borneo, New South Wales, and a few other places; but the only other source of supply of any importance is in British Guiana, where many small stones are found in the rivers in the interior. In the northern parts of the United States a few stones have been found singly in glacial deposits; these have been transported from some unknown spot

in Canada during the ice age. Finally, we may mention that small diamonds have been found in a few meteorites, showing that it may also be of cosmic origin.

For a time South Africa was the only large and important producer of diamonds, and the Union still produces more than half of the world's output. But now there are other competitors, and it is only with powerful combines and the holding of large stocks that prices can be kept up and, indeed, increased. As a result of the world's present economic crisis, the larger mines are now all closed down. The prices of stones vary widely according to their quality and size, a larger stone selling for much more per carat than a smaller stone. River stones fetch a higher average price than mine stones. Here a selection has already been made by Nature, flawed stones being more readily broken during their transportation with the gravels. Cost of production is of course great, and the work is highly speculative. But middlemen reap a rich harvest. High prices are really fictitious and depend largely on the seller and the buyer; and they have varied very considerably at different periods. Before the foundation of the De Beers Consolidated Mines in 1888 the average price of rough stones at the mines was £1 per carat. Since then it has ranged from £2 to £5, and for river stones up to £13 per carat. The price of cut stones is of course considerably higher, since there is a loss of material in cutting, the yield varying between 35 and 60 per cent of the weight of the rough stone; and there is another crowd of middlemen. In the year 1606 a cut brilliant of one carat fetched £22, and one of two carats £88. In 1878 the corresponding prices were £4½ and £14; and in 1933 £25 to £50, and £80 to £130 according to quality (and the purchaser). Comparing the present annual production of about seven and a half million carats (about a ton and a half of diamonds!) with what must have been the very meagre

production in 1606, there seems to be something wrong with these prices.

The carat weight has been mentioned so frequently in this chapter on diamond, that it is necessary here to give some explanation of its meaning. It is a most extraordinary fact that this unit of weight, which is used exclusively for weighing the most precious of materials, should have had such varying values in different countries, and even in the same country at different periods. At least six different kinds of carats have been used in England alone. The famous "Koh-i-Nur" was weighed in 1852 against an English carat having a value of 205.409 milligrams; whilst the still more famous "Cullinan" was weighed against an English carat with a value of 205.304 milligrams, and the cut stones against a Dutch carat of 205.712 milligrams. The "Florentine" diamond weighed 139½ Florence carats, 133⅔ Paris carats, and 133¼ Vienna carats (the true weight is 27.454 grams); but Florence and Vienna carats have not always been steady. Extreme values of the carat weight at different places have in modern times ranged from 188.6 to 213.5 milligrams. Old Indian weights no doubt showed even wider variations. There is a suggestion that the differences have been in part deliberate.

This extraordinary state of affairs has been finally settled by the general adoption of the "Metric Carat", equal to one-fifth of a gram or 200 milligrams. This was first adopted by the International Committee of Weights and Measures in Paris in 1907, and it was soon followed in most countries. Great Britain was the last to fall into line, the metric carat here becoming the legal unit of weight for precious stones in 1914. But the confusion will for ever remain when quoting from old books or when digesting old statistics. The metric carat is approximately 2½% less than the previous English carat. This means that the weight of a particular stone is expressed by a slightly higher number—a

point of advantage to the dealer when the price is so much per carat. Fractions of a metric carat are stated in decimals, instead of the awkward fractions of $\frac{1}{2}$ — $\frac{1}{64}$ as in the old system. Weights expressed in grams are easily reduced to metric carats by multiplying by five. Beware of grain weights. There are "diamond grains", "carat grains", and "pearl grains" of different values; and these are confused with "grains troy" and "grains avoirdupois" (which are of course identical). Such are the pitfalls of the English system of weights and measures.

The history and origin of the carat weight is of some interest. As an ancient unit of weight it was used for weighing gold as well as precious stones. But with gold the term carat is now used to express the degree of fineness as a ratio, or so many parts in 24. For example, 18-carat gold consists of 18 parts of gold and 6 parts of base metal. The Greek weight *κεράτιον* (keration) and the Roman *siliqua* were only slightly greater than the present carat weight. The Greek name refers to the horn-like shape of the fruit-pods (locust-bean or St. John's bread) of the carob or locust tree, which botanists call *Ceratonia Siliqua*. The seeds of this tree are remarkably constant in weight, and those taken from the ends of the pulpy pods are not smaller than those from the middle. Locust trees do not grow in England, so "After the statutes of Englande, the least portion of waight is commonly a Grayne, meaning a grayne of corne or wheate, drie, and gathered out of the middle of the eare" (Robert Recorde, 1542). The pretty scarlet and black seeds of the plant *Abrus precatorius* are used as weights at the present day by Indian goldsmiths as an equivalent of the Indian rati.

No book on precious stones is complete without some account of famous and historic diamonds. These accounts are usually copied blindly from book to book with little regard for the real facts, whilst an extra coat of varnish is given each time to sensational and stupid

stories. Glass models of many of these diamonds have been made for sale, but the different sets show some variations in size, shape, and colour of the models. In the following brief account of the largest and more important stones the weights quoted have been translated whenever possible into metric carats. This has presented many difficulties, for there has always been a tendency towards inaccuracy and exaggeration. A recent example is given in the reported weights of the "Cullinan" diamond at the time of its discovery, which ranged from $1\frac{1}{4}$ to $1\frac{3}{4}$ lb.

The "Cullinan" was found in the Premier mine, near Pretoria, Transvaal, on 25th January, 1905, less than two years after the mine itself had been discovered. A bright flash of light caught the eye of the surface manager from the wall of yellow ground 18 feet below the surface. The stone (Plate I) had the shape of a very irregular octahedron with one large cleavage surface, and was therefore probably only a portion of a still larger crystal. It measured $4 \times 2\frac{1}{2} \times 2$ inches and weighed 621.20 grams = 3106 carats = 1.3695 lb. avoirdupois. It was named after Sir Thomas Cullinan, the chairman of the Premier Company, and was purchased by the Transvaal Government in 1907 for £150,000 as a generous gift to King Edward VII. The perfectly clear and colourless stone was cleaved and cut in Amsterdam into nine larger (Plate I) and 96 small brilliants, weighing 530.20, 317.40, 94.45, 63.65, 18.85, 11.55, 8.80, 6.80, 4.40, and the 96 small brilliants together 7.55 carats, a total of 1063.65 carats, corresponding to a yield from the rough stone of 34 $\frac{1}{2}$ %. These are now with the crown jewels in the Tower of London, where they are on view to the public. The largest gem, measuring $2\frac{5}{16} \times 1\frac{1}{2}$ inches, is a pendeloque brilliant, and is much the largest diamond ever cut.

Other large stones, but of doubtful quality and presumably classed as bort, have been recorded from the

Premier mine, namely, one of 1683½ carats in 1912, another of 1500 carats in 1919, and another of 1195½ carats in 1924. Although the "Cullinan" is by far the largest single crystal of gem quality on record, its weight is exceeded by that of a mass of the black diamond, carbonado, which was found in 1895 near Lençoes in Bahia, Brazil. This weighed 631.9 grams = 3159.5 carats.

The next largest diamond is the "Excelsior", which was found in 1893 in the Jagersfontein mine in Orange Free State. It had a flattened form with irregular curved outline $2\frac{1}{2} \times 2$ inches, and a thickness of about 1 inch. At one end was a large flat cleavage surface showing that the crystal had been broken. The weight was 199.04 grams = 995.2 carats. Failing to find a purchaser, the stone was left intact until 1903, when it was cleaved and cut into twenty-one brilliants with a total weight of 373.75 carats (the largest weighing 69.68 carats), corresponding to a yield from the rough stone of 37½%.

The next largest gem diamond is the "Jonker", found quite recently, in January, 1934, by Jacobus Jonker, who worked his own small claim in the Elandsfontein alluvial diggings on a tributary of the Pienaars river near the Premier mine. This stone also has an irregular rounded form with a cleavage surface, suggesting that it is a broken crystal, and no doubt fractured by the volcanic eruptions in the Premier pipe. The weight is 726 carats. It was sold immediately to the Diamond Corporation for £75,000, and has since passed to an American dealer for almost double this amount.

Next we come to the "Jubilee", another large stone from the Jagersfontein mine in Orange Free State, found in 1895, and cut in 1897, the year of the diamond jubilee of Queen Victoria. It was a flattened and rounded octahedron measuring $5.5 \times 4.8 \times 3.1$ cm., and weighing 650.8 carats; and was cut as a brilliant

of 245.35 carats (Plate IV), and a smaller pendeloque brilliant of 13.35 carats. A stone of "over 600 carats" had been found earlier, in 1883 or 1884, in the Jagersfontein mine, but no information of this is available.

The "Imperial", also known as the "Victoria" or "Great White", appeared surreptitiously on the London market in 1884, having presumably been stolen from the mines and smuggled from the Cape. In all probability it came from the Jagersfontein mine. It was elongated and rounded with a cleavage at one end, and much like a gherkin in shape. The weight was 469 carats, and it yielded two brilliants of 184.5 and 20.5 carats.

The "De Beers" diamond, found in 1888 in the De Beers mine at Kimberley, differed from the preceding stones in being more regular in its shape, having the form of an octahedron with curved faces. It was a pale yellow stone weighing 440 carats, and yielded a brilliant of 234.5. Here the yield was much higher (53½%) than usual, the regular octahedral form of the stone being more favourable for cutting. Another similar stone, found at Kimberley before 1896, weighed 362 carats, and gave a brilliant of 205.1 carats, with a still higher yield of 56½%.

The "Stewart" was a river stone from South Africa found in 1872 in the Vaal. It weighed 296 carats and yielded a brilliant of 123 carats.

Many other larger stones have been found in South Africa, though several of these are not of fine gem quality, being off-colour or sold as bort. Sixteen stones of over 500 carats have been listed; those between 400 and 300 carats number 49; between 300 and 200 as many as 157; whilst the remainder each of over 100 carats number 1623. Indian diamonds, about which there has been so much mystery and romance, sink into insignificance.

Few diamonds of any size have been found in India during recent times. One of 69.7 carats was found in

1881 at Wajra Karur, near Bellary in Madras, and was cut as a brilliant of 25.2 carats. Information of the largest Indian diamond is based only on the account given by the French traveller J. B. Tavernier. This, the "Great Mogul", he saw in 1665 in the treasury of the Mogul emperor, Aurangzeb, as a cut stone of "280 carats". It was said to have been cut by a Venetian lapidary from a stone of "787 carats". But Indian-cut stones do not usually show such a great waste of material in the cutting. We do not know the value of these "carats", and there is no good evidence that the stone was really a diamond at all. Anyway, it has disappeared, either lost or stolen; and if really a stolen diamond it was no doubt recut as the "Orlov", or perhaps the "Koh-i-Nur". Another large diamond, the "Great Table" of "242 carats" mentioned by Tavernier, has likewise disappeared, or probably been recut. It is high time that the stories of these mythical stones disappeared from the serious literature on diamond. They might be forgotten, like the once famous "Braganza", a supposed diamond (more probably a colourless topaz or even rock-crystal) of 1680 carats from Brazil in the Portuguese crown jewels and valued at £224,000,000!

The "Koh-i-Nur" ("Mountain of Light") was appropriated in 1739 by Nadir Shah, the Persian conqueror of the Mogul Empire. In 1813 it came into the possession of the Rajah of Lahore, and with the annexation of the Punjab in 1849 into that of the East India Company. It was presented by the Company to Queen Victoria in 1850, and was shown at the Great Exhibition of 1851. It then had the form of an Indian-cut rosette with irregular surfaces at the back (fig. 42). The weight was 191.09 carats. The stone was then recut as a brilliant (fig. 43), reducing the weight to 108.93 carats. It is now set in the state crown of Queen Mary, and may be seen in the Tower of London. Unfortunately, when recutting this stone the proper proportions of a

brilliant were not observed. The spread was made as large as possible, but the depth was too shallow to bring out the full brilliancy of the stone. Plaster casts of the stone in its two forms of cutting, taken at Buckingham Palace in 1852, are preserved in the mineral collection of the British Museum.

The "Orlov" is an Indian-cut stone of irregular shape weighing 199.6 carats. It was given by Prince Orlov

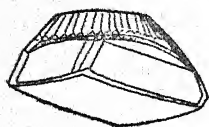


Fig. 42.—"Koh-i-Nur"
diamond, Indian-cut

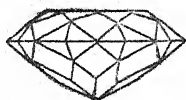


Fig. 43.—"Koh-i-Nur"
diamond, brilliant-cut

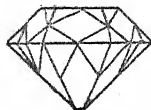
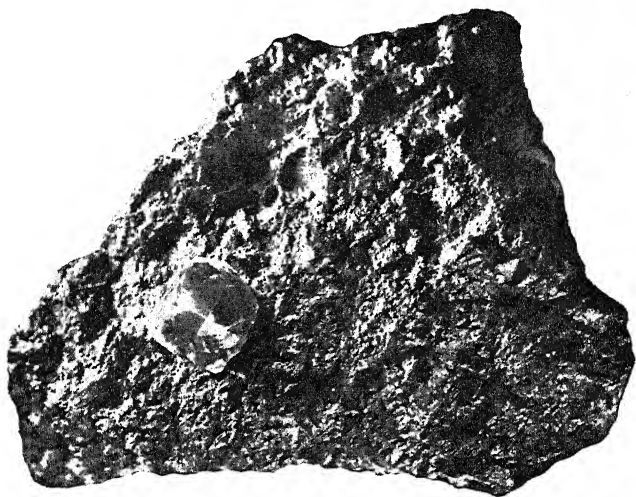


Fig. 44.—"Pitt"
or "Regent" dia-
mond, brilliant-cut

(All figures reduced $\frac{1}{2}$)

in 1773 to the Empress Catharine II of Russia, and until recently was in the sceptre of the Russian crown jewels. The "Moon of the Mountains" and the "Darya-i-Nur" ("Sea of Light") are probably identical with the Orlov, which itself was perhaps recut from the Great Mogul.

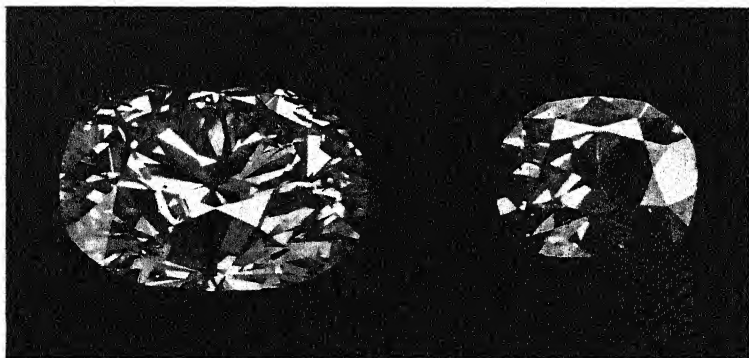
The "Shah", another Indian stone in the Russian diamond treasure, is one of the few engraved diamonds. It gives in Persian characters what may be taken as its true history. The first inscription gives the name of Nizam Shah, year 1000 (i.e. A.D. 1591); the second, the Mogul emperor, Shah Jahan, 1651; and the third, the Persian shah, Fath Ali, 1824. The stone is an



CRYSTAL OF DIAMOND IN THE "BLUE GROUND"

This specimen was given by Cecil Rhodes to commemorate the amalgamation in 1888 of the diamond mines at Kimberley. $\times 2$

British Museum

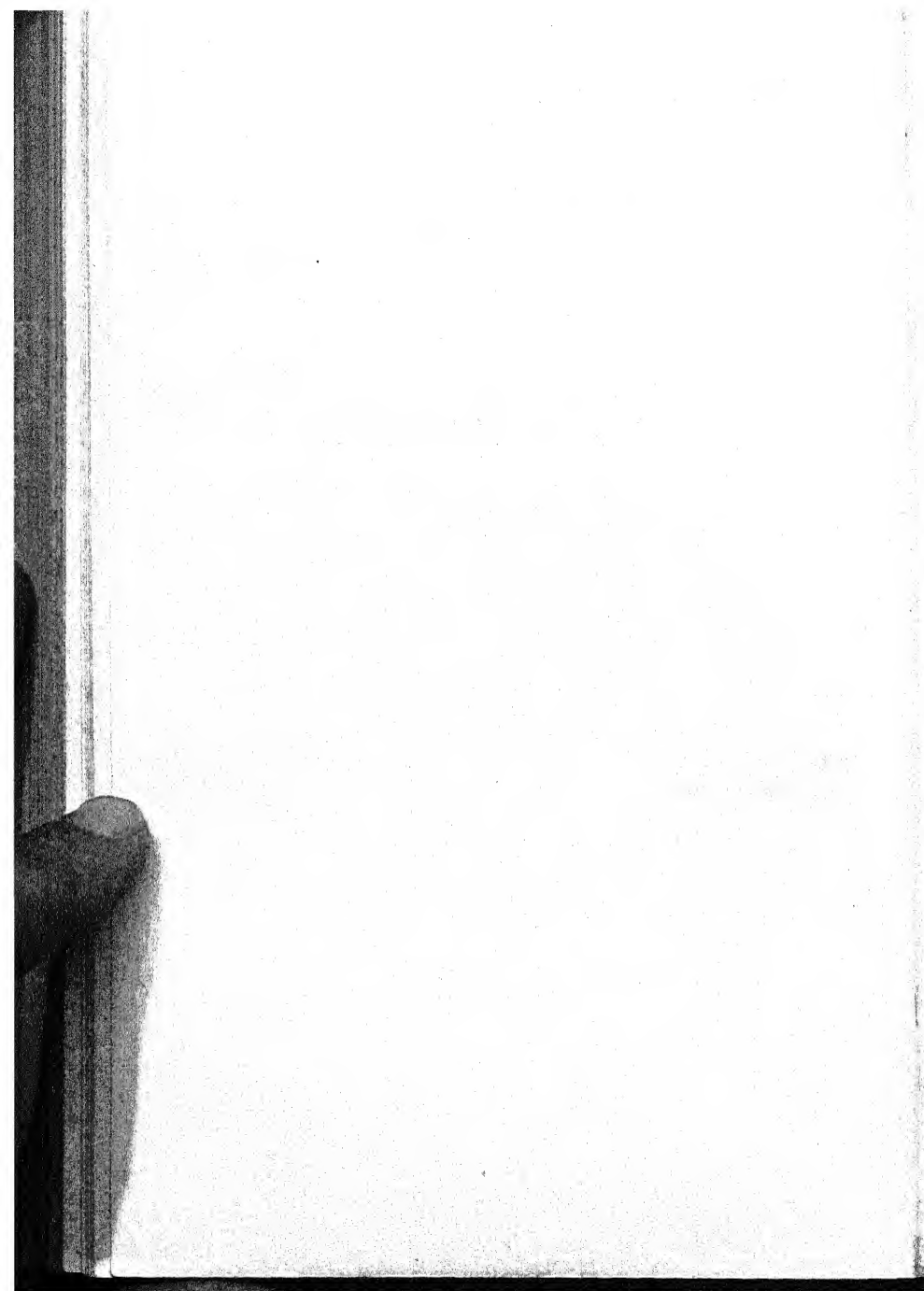


THE "JUBILEE" DIAMOND

(Actual size)

THE "HOPE BLUE" DIAMOND

(Actual size)



elongated octahedron with a few polished facets, and weighs 88.70 carats.

The "Florentine", "Grand Duke of Tuscany" or "Austrian Yellow", has been known in Europe since the fifteenth century and is no doubt of Indian origin. It is cut as a briolette, probably by Ludwig van Berquen in 1476 for Charles the Bold. It is a pale yellow stone weighing 137.27 carats, and is now in Vienna. The smaller "Sancy" diamond ($53\frac{1}{2}$ carats) is of the same type of cutting.

The "Pitt" or "Regent" (fig. 44) is said to have been found on the Kistna river in Hyderabad in 1701. It was bought by Thomas Pitt ("Diamond Pitt"), Governor of Fort St. George, Madras, for £20,000, and sold by him, still in the rough, to the Duke of Orleans, Regent of France, in 1717, for two million francs (according to another account £135,000). The rough stone weighed 410 carats, and it was cut as an extra deep brilliant of 135 carats, the work taking two years and costing £5000. Stolen with the French crown jewels in 1792, it was recovered, and is now exhibited in the Louvre in Paris. A leaden model of the rough stone and a glass one of the cut brilliant were in the collection of Sir Hans Sloane. These, together with models of the "Florentine" and "Dresden Green" diamonds, came to the British Museum in 1753.

Several other Indian diamonds have been described as famous, but we must now pass to the few from Brazil. The "Star of the South" was found at Bagagem in Minas Geraes in 1853, and had the form of a rhombic-dodecahedron with curved faces. It weighed 261.88 carats and was cut as a brilliant of 128.5 carats. Both this and the smaller "Dresden" were acquired by the Gaekwar of Baroda. The "Star of Minas", weighing 179.37 carats, was found at Bagagem in 1911. Other large diamonds have more recently been found in the Bagagem district: the "President Vargas" of 726.6 carats in 1938, and the "Darcy Vargas" of 460 carats

in 1939. Still more recently large stones of good quality have been found in Sierra Leone, West Africa, where two small stones were first found in 1931: two of 249 $\frac{1}{4}$ and 532 carats in 1943, and one of 770 carats in 1945, which comes high in the list of the world's famous diamonds.

Coloured diamonds, especially those of large size, are rare. The "Hope Blue" (Plate IV), so named from a former owner, Henry Philip Hope, a London banker, was described in the catalogue of his collection in 1839. Its unsymmetrical form suggests that it had been recut from a larger pear-shaped brilliant stolen with the French crown jewels in 1792, which had been brought from India by Tavernier. It weighs 45 $\frac{1}{2}$ carats and is of a dull slaty-blue colour, though perfectly transparent. It was sold in Paris in 1909 and is now in America. The "Dresden Green" is a clear apple-green brilliant of 41 carats, and no doubt also of Indian origin. It was purchased in 1743 by August the Strong for the Saxon crown, and is still to be seen in the Green Vaults at Dresden. The "Tiffany Yellow", the property of Tiffany & Co. of New York City, is a canary-yellow brilliant of 128 $\frac{1}{2}$ carats. It was found about 1878 in the Kimberley mine at Kimberley, South Africa. Another yellow diamond from South Africa is the "Tennant", a brilliant of 68.0 carats. The "Colenso" diamond in the mineral collection of the British Museum is perhaps the largest uncut natural crystal to be seen in any public collection. It is a pale yellow, well-shaped octahedron showing delicate triangular markings on the faces. The weight is 26.6290 grams (133.145 carats). It was presented in 1887 by John Ruskin in memory of his friend John William Colenso, "the loyal and patiently adamant first Bishop of Natal". A rose-coloured diamond, the "Cross of the South", weighing 118 carats, is said to have been found in Brazil in 1929.

Numerous attempts have naturally been made to

produce by artificial means the costly diamond from the common and abundant material carbon. This has often been asserted to have been accomplished, though only as particles of microscopic size. The results of the experiments are, however, extremely doubtful. The alleged diamonds were so small that they could not be submitted to really decisive tests. The test of hardness was mainly relied upon; but it is now known that various carbides (e.g. silicon carbide or carborundum) have a hardness of over 9 on the scale, and are capable of scratching corundum. The minute crystals obtained by J. B. Hannay in 1880 have now been examined by the rigorous X-ray method and proved to be really diamond; but his results have never been repeated. The dictator who can arrive at the secret of marshalling black-shirted carbon atoms into the correct positions to form a pure and colourless crystal of diamond will indeed become notorious.

KEY TO THE CHARACTERS OF DIAMOND

Crystals, cubic; rounded forms common. Composition, carbon. Specific gravity, 3.5. Hardness, 10. Refractive index, 2.417 (yellow light). Dispersion, 0.06 (red to violet). Optically isotropic (sometimes feeble birefringence due to strain). No pleochroism. Colourless or variously coloured. Largest crystal, the "Cullinan" diamond, 3106 metric carats. Varieties: bort and carbonado. Localities: South Africa, Brazil, British Guiana, India.

CHAPTER XIII

Corundum and its Colour Varieties— Ruby and Sapphire

RUBY, sapphire, and emery were known to the ancients, but it was only with the rise of scientific mineralogy that these were found to be really the same kind of stone, differing only in their colour (red, blue, black) and degree of transparency. As we have seen in a previous chapter, this difference in colour is a matter of little importance. A hat or a tie still remains a hat or a tie whether it is red, blue, or black. The French crystallographer Romé de l'Isle found in 1783 that crystals of ruby and sapphire had the same angles between corresponding faces, although the relative sizes of the faces themselves may be variable. This gives a difference in the "habit" of the crystals; and we usually find tall crystals of sapphire and flat crystals of ruby, just as there may be tall hats and flat hats of all sorts of funny shapes. The next French crystallographer, the Abbé Haüy, therefore brought ruby and sapphire together as one species to which in 1796 he gave the name *télésie* or *telesia*, meaning perfection. This name found little favour and the species was usually at that time called sapphire, ruby being distinguished as "red sapphire" or "ruby sapphire". According to the early analyses of the Swedish chemist T. O. Bergman (1735-84), 100 parts of ruby contained 40 of argill, 39 of silice, 9 of mild calcareous earth, and 10 of iron, whilst sapphire was composed of the same

constituents in the proportions 58, 35, 5, and 2. We now know that both really consist of very nearly 100% of his argillaceous earth (i.e. the essential earth of clay) which is now called aluminium oxide or alumina. The German chemist M. H. Klaproth had already in 1795 found 98.5% of alumina in sapphire. But it was left to an English mineralogist to clear up the matter finally, and it was he who first introduced in 1798 the now well-known name corundum for this mineral species. This was the Right Honourable Charles Francis Greville, also notorious as one of the lovers of Lady Hamilton. The specimens of Indian corundum which he described in 1798 are still preserved in the British Museum collection of minerals.

In olden times most corundum (apart from emery), and no doubt all ruby and sapphire, came from the East Indies. The rough material, used for grinding and engraving, was known as adamantine-spar because of its great hardness. The name corundum itself is also of Indian origin, *kurund* in Hindi, and *kuruvinda* in Sanskrit. The name had been earlier mentioned in English by John Woodward in his *Catalogue of Foreign Fossils* (1728), but on three pages he spells it differently each time. His entries are worth quoting:

Nella Corivindum is found in Fields where the Rice grows. It is commonly thrown up by Field Rats, and us'd as we do Emery, to polish Iron.

Tella Convindum. 'Tis a talky Spar, grey, with a Cast of Green. It is used to polish Rubies and Diamonds. *Fort St. George* [now Madras].

Nella Corivendum is found by digging at the Foot or Bottom of Hills about 500 Miles to the Southward of this Place [Fort St. George, East-India]. They use it, as Emery, to clean Arms, &c. It serves also to grind Rubies, by making it like hard Cement, by the help of Stick-Lac mix'd with it.

These specimens are still preserved in the Woodwardian collection at Cambridge. Only the second of them is what we now know as corundum, the other two

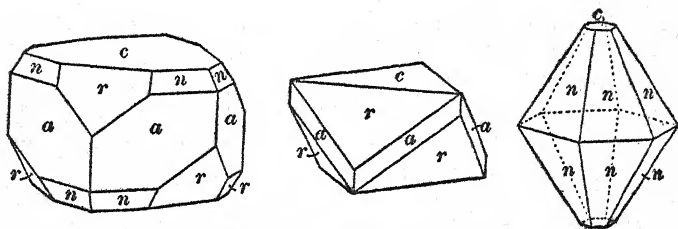
being garnet. But even at the present day these two minerals are sometimes confused; and what is sometimes sold as emery paper is really garnet paper.

The name corundum is now universally used by mineralogists, with only slight variations in different languages—French and Spanish, corindon; German, Korund. The English form with the ending *um* (given at a period when new chemical elements were being discovered and named) is perhaps rather unfortunate, and to most people appears to be rather strange: they immediately suggest conundrum. The guard in a famous collection of minerals, when asked by a visitor where ruby could be seen, pointed to the covering label corundum, apologetically explaining that was where the curator put things he did not understand.

But we must now come to a more serious, though scarcely exhaustive, study of the mineral under discussion. Corundum crystallizes in the rhombohedral system (p. 36). A selection of crystals typical of the ruby and sapphire varieties is represented in figs. 45–47. These are combinations of the following four crystal-forms. Basal pinakoid (*c*) consisting of a pair of parallel faces, one face alone being spoken of as the basal plane. Rhombohedron (*r*) of six faces in three parallel pairs. Hexagonal prism (*a*) of six faces in three parallel pairs and perpendicular to the basal plane. Hexagonal bipyramid (*n*) of twelve faces in six parallel pairs. The figures are drawn in “parallel perspective” with the vanishing point at infinity. All parallel edges on the crystals are therefore represented by parallel lines. It will be noticed that all lines formed by the intersection of corresponding faces are strictly parallel in the three figures. Although the different faces show a variation in their relative sizes, yet their directions remain the same. Measurement of the angle between the normals to the faces *c* and *r* gives a value $57^{\circ} 34'$, which is taken as the fundamental constant for corundum, different from that on any other mineral. From

it all the other angles can be calculated, e.g. $cn = 61^\circ 11'$. If we measure either of these angles on a doubtful crystal of this type we know for certain that we are dealing with corundum.

Fig. 46 differs from fig. 45 in the absence of the n faces and the smaller size of the a faces. If the latter are also absent, then we have a solid bounded by eight faces (six rhombohedron faces and two basal planes). Such a crystal of ruby may be strikingly similar in appearance to a flattened octahedron of red



Figs. 45-47.—Crystals of Corundum
Figs. 45 and 46 Ruby habit. Fig. 47 Sapphire habit

spinel, and the two may very readily be confused. But in ruby we find the angles $cr = 57^\circ 34'$ and $rr = 93^\circ 56'$, whilst in spinel all the angles between adjacent faces are $70^\circ 32'$. Or, again, if only rhombohedral faces are present the crystal will have very much the appearance of a cube, but with angles of $93^\circ 56'$ instead of 90° .

The flatter habit of crystals represented in figs. 45 and 46 is more typical of ruby, whilst taller crystals as in fig. 47 are as a rule more typical of sapphire. The latter often show a number of still steeper hexagonal pyramids with angles to c ranging up to $85^\circ 30'$. A combination of these in a series of steps gives rise to characteristic barrel-shaped crystals; and the faces of such crystals are usually striated and grooved parallel to the horizontal edges. The other faces on the crystals may also show characteristic surface

markings, especially triangular markings and pits on the basal plane, but these cannot be described here in detail. Mention must, however, be made of markings of another type which are often to be seen on the faces of the crystals as fine rulings parallel to faces *c* and *r*. This is due to a lamellar twinning, and sometimes the crystals may be readily broken in these directions, giving smooth surfaces. This is, however, not a true cleavage, and is described as a "parting" due to the twinning. It is as if the crystal had been cut up into excessively thin slices parallel to the faces *c* and *r*, and alternate slices turned over, and then the whole pile stuck together again. This lamellar twinning has probably been brought about by earth pressures during mountain building. It is the primary cause of the "silk" in ruby and the bright rays reflected by "star-stones". Although this kind of twinning is very frequent in corundum, simple contact twins are only rarely found. These consist of two crystals grown together in a certain regular manner and with their principal axes inclined to one another at an angle of $64^{\circ} 52'$ (i.e. twice our angle $cr = 57^{\circ} 34'$ subtracted from 180°). A smaller crystal may sometimes be seen branching out like a bud at this angle from the side of a larger crystal.

Plate V represents an actual crystal of ruby of exceptionally large size for one approaching gem quality. It weighs 690 grams (= 3450 carats) and measures $4\frac{3}{4}$ inches across. It comes from the ruby mines at Mogok in Upper Burma, and has recently been acquired for the British Museum collection of minerals. The reader may well say that this crystal does not look at all like the drawings in figs. 45 and 46. Only exceptionally do crystals of any kind display the model-like regularity shown in the figures. But they always show the true symmetrical disposition of the faces and with the correct angles between these. This ruby crystal grew in solid marble, and its regular growth was cramped

and crippled. The specimen was photographed in light reflected from the basal plane, shown in the picture as a number of light triangular areas. Each portion of the whole crystal independently formed its own basal plane, but all in exactly the same parallel position, though not in the same geometrical plane. Turning the crystal about an axis parallel to one or other of the three edges of these triangles through an angle of $57\frac{1}{2}^\circ$ (our angle *cr* again), another series of small facets shine up by reflected light over the whole area of the crystal. Similarly, in other positions at 61° from *c* the faces *n* (fig. 45) become evident.

Crystals of gem corundum are smaller in size than the one just mentioned. But opaque, dull-coloured crystals may be considerably larger. The largest crystal on record weighs 335 lb., and measures 2 feet 3 inches high and 1 foot 3 inches across. It has the form of a hexagonal bipyramid (fig. 47) and is opaque with a bluish-grey (scarcely sapphire-blue) colour. It was found in the corundum mines near Leydsdorp in northern Transvaal, and is now exhibited in the Geological Survey Museum at Pretoria. The largest corundum crystal in the British Museum collection of minerals is a rough hexagonal prism 10 inches high and 7 inches across, weighing 34 lb. This shows a good red colour in parts, and from a rosy point of view it might be described as a ruby. It came from Corundum Hill in Macon County, North Carolina, a locality that has yielded ruby of gem quality.

These two large crystals, one with a bluish and the other with a reddish tinge of colour, illustrate the point previously mentioned as to the difference in habit of crystals of sapphire and ruby. In sapphire there is usually a development of a series of steep hexagonal pyramids; whilst in ruby there is usually a large development of the hexagonal prism and basal planes, and in gem ruby the crystals are often flat with a short prism. There must be some reason for such a

difference. When crystals of various kinds are grown artificially from solution, it is known that their habit is influenced by the presence of various colouring matters or other substances in the solution. It is therefore probable that in corundum there is some connexion between the shape of the crystals and the impurities that gave rise to the colours of ruby and sapphire. This question is worthy of further investigation.

The essential characters of corundum have already been listed in the reference tables previously given. Chemically, the mineral consists of aluminium oxide or alumina (Al_2O_3). When ammonia is added to a solution of alum a white jelly-like precipitate of aluminium hydroxide ($\text{Al}_2(\text{OH})_6$) is obtained. This when dried yields a snow-white powder of alumina, which is the material used for the manufacture of artificial corundum gems. In the absence of any added colouring matter the crystalline product is colourless and water-clear, and such stones are also found in nature. Analyses of native stones of gem quality usually show the presence of about one per cent of iron oxide, together with a small amount of chromium oxide in ruby and of titanium oxide in sapphire.

In hardness corundum comes next to diamond, being the next hardest known mineral. But it is exceeded by carborundum and some other artificially produced carbides. Owing to this high degree of hardness corundum finds an important application as an abrasive agent for grinding and polishing, when applied in a powdered form to paper (emery paper) or in the form of wheels or hones. The powder in different grades of fineness is used by lapidaries for grinding gemstones. Emery, which has been obtained since ancient times from Greece and Asia Minor, is a black and granular form, consisting of a mixture of grains of corundum, with magnetite, spinel, and other minerals. When examined under the microscope some of the small

grains of corundum are seen to be of a good sapphire-blue colour. Another important technical application of corundum, depending on its hardness, is for pivot supports in delicate instruments; for example, the jewel bearings in watches. Here smaller stones of poorer gem quality are made use of.

The specific gravity of corundum varies only slightly from 4.0 (3.95-4.05 for clear crystals), and this variation is no doubt accounted for by the presence of cavities and impurities. This high density is rather surprising when we consider that corundum contains only the light metal aluminium (sp. gr. 2.6) and the gas oxygen, which at normal temperature and pressure has a density of 0.0014 compared with that of water (liquid oxygen ranges from 0.6 to 1.3 according to the very low temperature).

The optical characters are those typical of a uniaxial crystal of negative sign (p. 49). When crystals such as those shown in figs. 45 and 46 are viewed through the prominent basal plane (c) under the microscope in parallel light or with the dichroscope, they will behave like an isotropic cubic crystal; and under these conditions they are indistinguishable optically from spinel. We have already remarked on the similarity in form shown in fig. 46 to a crystal of spinel. But in convergent polarized light, if the crystal is not too thick, a uniaxial interference-figure (Plate II) will at once distinguish the two minerals. Through all other faces the crystals will be seen to be birefringent and dichroic; though, as previously explained, these effects are seen at their maximum when the crystal is viewed through the prism faces (a). The refractive index (ϵ 1.760, ω 1.768) and the dispersion (0.018) are much less than in diamond, consequently corundum gems are less brilliant and do not flash prismatic colours to the same extent. In coloured stones the absorption for the ordinary ray (ω), travelling in the direction of the optic axis or principal crystallographic

axis (set vertically in figs. 45-47) is greater than for the extraordinary ray (ϵ). Consequently a deeper colour is seen in this direction than when the crystal is viewed through the prism faces. To bring out the colour to the best advantage a faceted gem should therefore be cut in such a direction that the table facet is parallel to the basal plane (c) of the crystal. But a very dark stone may with advantage be cut with the table facet parallel to a prism face. The pair of dichroic colours will of course depend on the colour of the crystal. In the best rubies the ordinary ray-colour (ω) is deep red with a violet tinge, and the extraordinary ray-colour (ϵ) is a light yellowish red; the face-colour seen through the prism being a combination of these. In the best sapphires the corresponding colours are ω deep blue, sometimes with a violet tinge, and ϵ paler greenish or yellowish blue.

Now we come to the question of colour, a matter of prime importance from a gem point of view; but an accidental character of trivial importance from a mineralogical point of view. In addition to perfectly colourless and black stones, the range of colours shown by corundum is really surprising. They range through the whole spectrum—red, orange, yellow, green, blue, indigo, violet, with varying shades and intensities. But beyond this visible spectrum selective absorption extends away into the ultra-violet and the infra-red, and for all we know as far as X-rays and radio-waves.

Red corundum has long been known as ruby, from the Latin *ruber*, red. But by the Romans it was included (and confused) with other hard red stones (spinel and garnet) under the name *carbunculus*, and by the Greeks under the name *anthrax*, both of which signify a glowing coal. The name ruby is more recent. The earliest reference that I have been able to find is dated 1310 in the big *Oxford Dictionary*. In 1380 Chaucer wrote "lyke ruby ben your chekys rounde".

As late as 1652 Thomas Nicols in his *A Lapidary: or, the History of Pretious Stones* (Cambridge, 1652) says:

"The true *Carbuncle* or *Ruby* is a transparent jewell of the colour of pure vermillion or crimson; by how much the more fiery it doth appear in its extremity, so much the better it is. . . . A *Carbuncle* is nothing else but a great *Rubine*, and a great *Rubine* is thought worthy of the name of a *Carbuncle*."

The colour may range from deep red through various shades to pale pink. Stones of a deeper colour usually show a purplish tinge (expressed as a blue line in the absorption spectrum); whilst lighter ones often have a yellowish tinge. The colour of the best rubies is said to be "pigeon's blood red", a statement slavishly copied parrot-like from book to book. It seems inevitable that strange ideas and stupid superstitions must linger with precious stones.

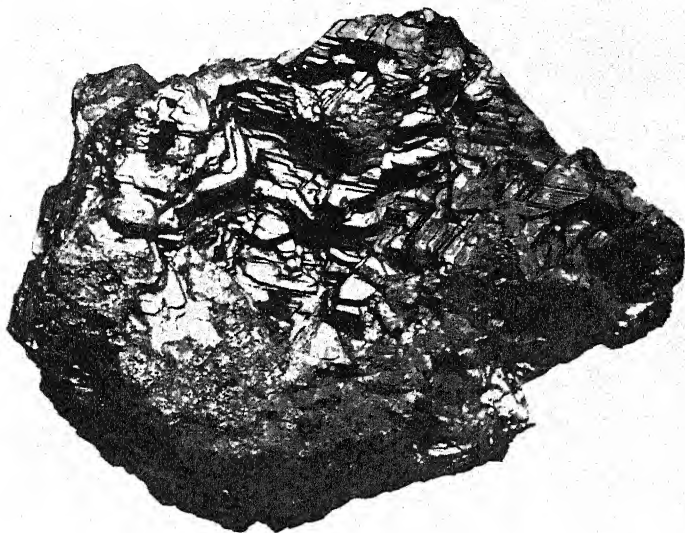
Leaving the other colours for the time being and coming to the other end of the spectrum, we have the blue of sapphire. This is a much older name than ruby. The names sappir in Hebrew, saffir in Persian, and *σάπφειρος* in Greek have always signified a blue stone; but this was lapis-lazuli and not the sapphire (French and German, saphir; Italian, zaffiro; Russian, safir) of the present day. The latter was known to the Greeks and Romans as *ῥάκινθος*, hyacinthus. The colour may range from inky blue through sky-blue to a pale greyish blue. Velvety blue and cornflower-blue are praised by connoisseurs.

The names ruby and sapphire have at the present time a definite meaning in all languages, with only slight variations in their spelling. The terms ruby-red and sapphire-blue also have a quite definite meaning. But when we come to corundum of other colours there is much unfortunate confusion in the names that have been applied. Beautiful shades of yellow are met with. A fine pair of gems, orange-yellow and lemon-yellow in colour, has recently been

bequeathed to the mineral collection of the British Museum with the Clarke-Thornhill collection of gems. These are labelled yellow corundum, which truly describes their nature. But such stones are very often called "yellow sapphire", which is surely a misnomer. They are also often called "oriental topaz", which is still worse. There is not the slightest connexion or relationship between the minerals corundum and topaz, and yellow is *not* a characteristic or typical colour of topaz. Names of a similar misleading character have been wilfully applied to green corundum, violet corundum, and colourless corundum. I refrain in this place from propagating such names.

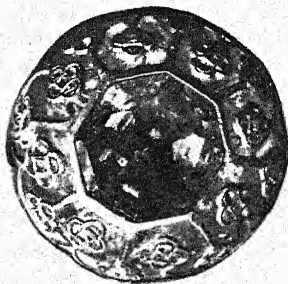
Two other specimens of gem corundum in the British Museum collection of minerals may be mentioned in this place. One is a deep blue sapphire (Plate V) which came to the museum in 1753 with Sir Hans Sloane's collection. It is a native Indian rose-cut stone with an octagonal outline $\frac{3}{4}$ inch across and weighing 31.5 carats. Set in a hemisphere of rock-crystal inlaid with bands of gold and small rubies and emeralds, it was evidently intended for wearing in a turban. The second is an uncut crystal of ruby weighing 167 carats, which was presented by John Ruskin in 1887 in memory of Sir Herbert B. Edwardes (1819-68), soldier-statesman in India, and is called the "Edwardes ruby".

Very striking colour effects are shown when ruby is exposed to ultra-violet rays. The crystals or cut stones are seen to glow with a brilliant red light, as if they were on fire. They then fully justify the Greek and Roman names *anthrax* and *carbunculus*, which meant a glowing coal (cf. anthracite). Removed from the influence of the ultra-violet rays, the red colour shown by the stones themselves is very poor in comparison. This curious phenomenon is known as fluorescence. The crystal is here acting as a transformer of the wave-length. The invisible rays of short wave-length are



ROUGH CRYSTAL OF RUBY FROM BURMA: $\times \frac{3}{4}$

British Museum



SAPPHIRE SET IN A HEMISPHERE OF ROCK-CRYSTAL
INLAID WITH GOLD, RUBIES, AND EMERALDS

(Sir Hans Sloane's collection, 1753. Actual size)

British Museum

Facing p. 150

absorbed and given out as longer waves with a wave-length corresponding to that of red light. Ladies who wish to display their rubies to the best advantage should move in circles of shorter wave-lengths, but unfortunately the wearer would then be invisible. But wonderful effects can be obtained by slightly greasing the face and hands, and wearing garments coloured with special dyes. (A beautiful blue glow is given by a white fabric which has been dipped in a solution of quinine; and other colours by aniline dyes.) Finger-nail stains and polishes show up to perfection in ultra-violet rays; and teeth glow like pearls (with black gaps corresponding to any that are false). A really spectacular lady could easily be built up on these lines. But we must return to the subject of corundum. Different stones are very capricious in their behaviour in the ultra-violet rays. Some rubies show only a dull red glow and others a yellow; but clear red artificial gems are always dependable. Yellow gem corundum and some sapphires give a yellow glow. But there is no general rule: each stone must be tested separately, and some may not respond at all.

There are two special features closely related to one another which are often shown by native corundum, but which are not seen in artificially produced gem corundum. These are known as "silk" and "asterism". There may be seen in the stone patches with a silky lustre, which are usually of a rather paler colour. When these are examined with a magnifying lens a parallel series of fine fibres will be seen. In asterism there is a display of a six-rayed, sometimes twelve-rayed, star of light on the surface of the stone. This can sometimes be seen on the basal plane of a natural crystal; but it is shown to the best advantage when the stone is cut in a cabochon or dome-shaped form the base of which coincides with the basal plane of the crystal. Such stones are known as *asteria*, *star-ruby*, and *star-sapphire*. This also depends on fibrous

enclosures in the stone, but here they are much finer and are arranged in three directions at 60° . The fibrous enclosures in the crystal follow the directions of the planes of lamellar twinning previously mentioned. These are planes of weakness in the crystal, and along them the material has suffered some alteration by the action of percolating solutions. Corundum when preserved in collections and worn as a gem may seem to be a lasting and permanent material, and so it would be if the conditions of its environment always remained the same. But when buried deep in the earth's crust under different conditions of temperature and pressure, and in the presence of rock juices different from those from which the crystals originally grew, then during long periods of time (not to be measured on the historical scale of kings and wars) even corundum may succumb. In fact, we often find crystals of corundum completely changed into other minerals, such as mica, spinel, kyanite, &c. One of these has been named corundophilite, meaning friend of corundum, because the two are often found in association; but it is really an enemy of corundum and leads to its destruction.

Now silk and asterism are indications of the commencement of this change; if it proceeds farther the stone is completely spoilt. It proceeds along the planes of weakness produced by the lamellar twinning, which itself was produced by earth pressures in mountain building—the best star-rubies and star-sapphires are from mountainous regions. The fine tubular cavities at the intersection of the different sets of planes of lamellar twinning may be filled with the alteration products or they may be completely empty or filled with liquid. In some cases the material of the fibres can be identified as the mineral rutile. This may have been introduced by the solutions which brought about the alteration; or it may have been included by the crystal at the time of its growth; or it may have been thrown out from "solid solution" as the crystal cooled down

to another temperature. There has been considerable discussion as to the origin of asterism in corundum and other minerals; and we must bear in mind that similar appearances are not always due to the same causes. A natural stone showing silk or asterism is at once distinguished from an artificial corundum. But it is quite likely that if the latter were subjected to an intense shearing stress, and then acted upon by suitable chemical reagents, a similar result might be obtained.

The constituents, aluminium and oxygen, of corundum together build up more than half of the earth's crust (oxygen 46·7, silicon 27·7, aluminium 8%). But they are usually combined with silicon to form the important alumino-silicates—clays, felspars, and other rock-forming minerals. Corundum cannot therefore be formed in a rock that contains an excess of silica (as quartz), but only in one that contains a large excess of alumina over silica. This accounts for the limited distribution of corundum, which is really not a common mineral, though in a few places rough material has been mined in considerable quantities for use as an abrasive. The rocks in which it is found include the rarer types of syenite, peridotite, and serpentine, as well as some crystalline schists and crystalline limestones (marbles). These rocks belong to two classes, igneous rocks and metamorphic rocks. In the former the corundum has crystallized from a molten magma and is of igneous origin. In the latter it is of metamorphic origin, being formed by the reconstruction of pre-existing minerals under high temperature and pressure, while the rock remained in a solid state. Sometimes it has been formed in blocks of shale or clay-slate when these have been torn from the walls of rock crevices by the intrusion of a molten magma beneath the earth's surface. This foreign material may have been melted down, so supplying the necessary excess of alumina; or the blocks may have been baked

to such an extent that the alumina recrystallized as corundum in the blocks themselves. In this way, in the Island of Mull, were formed the only sapphires known to occur in the British Isles; but they are very small and of no use as gem-stones. Only two or three other authentic occurrences of corundum as crystals of microscopic size have been recorded from the British Isles.

Localities for gem corundum are few and far between, and except in a few cases the stones can be collected only as water-worn crystals and pebbles from the river gravels of the district. The stones found vary enormously in quality (and price). The best rubies come from Burma; and the best sapphires, together with gem corundums of other colours, from Ceylon. But this is not to be taken to mean that *all* rubies from Burma and *all* sapphires from Ceylon are better than those from other localities. Some rubies from North Carolina are better than some rubies from Burma. Sapphires of good quality are also found in Kashmir. Both ruby and sapphire, often rather dark in colour, come from Siam; dark blue and greenish blue stones from Australia; and paler "fancy stones" from Montana.

In Ceylon the principal gemming districts are in the neighbourhood of Balangoda, Rakwana, and Ratnapura, to the south of Adam's Peak, in the south central portion of the island. Ratnapura, which in Sinhalese means "City of Gems", is the trading centre. In the deep narrow valleys pits are sunk in the alluvial deposits at the sides of the streams. After penetrating mud, clay, and sand to varying depths, the gem-bearing gravel, called "illam", is reached. This has a thickness of five to thirty feet and rests on the bed-rock. The small pits are worked by small gangs of natives using very primitive methods for bailing out water, supporting the sides of the pits, and keeping back the flow of mud. The excavated "illam" is washed free from mud in the neighbouring stream in shallow baskets

made of closely woven strips of bamboo. The clean gravel is then sorted over and any gem-stones picked out. Not only sapphire, but also gem corundum of various colours, including some ruby, usually of a rather pale colour, and several other kinds of gem-stones, as well as gold, are so collected from these gravels. The other gem-stones include zircon, chrysoberyl (cat's-eye and alexandrite), spinel of various shades of colour, beryl (aquamarine), topaz, tourmaline, garnets of various kinds, and quartz varieties (amethyst, citrine, &c.). Gem-stones and gold are also collected by dredging in the streams themselves; and the high-level gravels on the sides of the valleys are also sometimes worked. The work is very haphazard and is done entirely by the natives themselves. There could scarcely be any systematic working on a large scale. One pit may strike a lucky patch, whilst another close by may be almost barren.

The rocks of the district are ancient pre-Cambrian (Archæan) gneisses and schists with some bands of white marble and intersected by later dikes of white and red pegmatite. Opaque corundum is known to occur in some of the gneissic rocks, but it is only quite recently that the gem corundum has been traced to a white quartz-free pegmatite, and aquamarine has been found in situ in a quartz-bearing pegmatite. It appears that practically all the gem minerals have been derived from these white pegmatites, but they are not workable propositions. There is no evidence that any have come from the white marble (as in Burma).

In Upper Burma the principal mining district is around Mogok. Here we find the same complex of ancient crystalline rocks as in Ceylon. But here the home of the ruby and of red spinel is definitely in the extensive bands and lenticles of white crystalline limestone or marble. Specimens showing crystals of ruby embedded in this rock may be seen in the best mineral collections. This is a rock of metamorphic origin.

It was no doubt originally deposited as an ordinary limestone in slightly muddy water in some ancient sea. When subsequently buried deep in the earth's crust and subjected to intense pressure and high temperature, the calcium carbonate slowly recrystallized as calcite, and the alumina, from the mud, as corundum. By a fortunate chance just the correct proportions of iron and chromium were also present to impart the best ruby-red colour.

The ruby mines of Burma must be very ancient. They seem to have been first heard of in Europe in the fifteenth century, and they were mentioned by J. B. Tavernier in the seventeenth century; but they had been rarely if ever visited by Europeans before the annexation of the country in 1886. Thousands of crudely cut rubies set in the Burmese regalia, taken at that time from the palace of King Theebaw at Mandalay, may now be seen in the India Museum in London. At that date the mines were leased to an English company, and mining was conducted on an extensive scale with modern methods. But since 1931 work has been done only on a small scale by the natives themselves, using again their old primitive methods.

Only very occasionally are rubies taken out of the solid rock, since here they are very sparingly and sporadically distributed. Nature has, however, kindly broken down enormous quantities of the rock, leaving the gem-stones in the more easily worked debris. Some of the workings are in mud-filled crevices and caverns, such as are well known in limestone districts, having been formed by the solution of the rock by surface waters containing carbon dioxide. Similar residual deposits from the limestone are also worked on the hillsides. But the principal workings are in alluvial deposits in the valley bottoms, and here the conditions are much the same as in Ceylon. These gem-bearing gravels, locally called "byon", contain a varied assortment of stones, derived not only from the

limestone but also from other rocks in the district. They have, in fact, yielded an even greater variety than in Ceylon; including ruby, sapphire, spinel, chrysoberyl, tourmaline, garnet, zircon, beryl, quartz, scapolite, apatite, danburite—indeed, most gem-stones but diamond. The stones of course vary very widely in their quality, and the bulk of the concentrates can only be used for gravelling roads and paths. It is said that some quite nice stones can be picked up on the roads around Mogok. But even if not of gem quality, the different kinds of stones have a mineralogical interest, and a careful study of them would no doubt tell us more about their origin, and possibly also give indications as to where to search for more.

In Kashmir the conditions are again rather different. The sapphire mines are situated near the village of Soomjam in the Zaskar Range at an altitude of 14,950 feet. The old mine discovered in 1881 became exhausted, but others were found close by in 1927. Here the sapphire, together with grey corundum and some of a pink colour, is found in pockets in kaolin (china-clay), and it can be readily extracted from the soft clayey matrix. This kaolin has resulted from the weathering in place of pegmatite veins traversing schists and crystalline limestone. Red and green tourmaline and beryl have also been found in the same district. In the mountainous region farther to the west, in the Afghan province of Badakshan, there are ancient ruby mines near Jagdalak, which were visited by Marco Polo in the thirteenth century. Here the occurrence is the same as in Burma, ruby being associated with red spinel in a crystalline limestone. It seems more likely that in the olden days rubies came from here rather than from Burma.

In Siam, ruby and sapphire are found together and with zircon in the provinces of Chantabun and Krat in the south-east. But they are known only in alluvial deposits. They are often rather deep in colour, some-

times almost black. In Australia dark blue and dark green gem corundum is found, also with zircon, in river gravels at Anakie in Queensland, and in tin-bearing gravels in the New England district in New South Wales.

Africa does not appear to have yielded any gem corundum, except a few small crystals of various colours from the Somabula diamond field in Southern Rhodesia. The "Cape ruby" from the South African diamond mines is really garnet. In the United States of America corundum has been mined to some extent at a few places, and with the rough corundum some material of gem quality has been found. A few rubies of good colour have been so produced at Corundum Hill and Cowee Creek in Macon County, North Carolina. In Montana gem corundums have been found in the streams around Helena, and for a time they were mined in a weathered andesite dike at Yogo Gulch. These are of various attractive colours, but rather pale.

The gem corundum, now so skilfully produced in large quantities (a ton a day) by the crystallization of alumina under artificially controlled conditions, is more uniform in character, clearer, and shows a much wider range of very attractive colours than the gem corundum made by Dame Nature. For technical purposes it is more reliable. The pretence that it is inferior as a gem is only because it can be produced so cheaply, giving rise to trade competition. The stones are identical in all essential characters, the real difference is in their mode of origin. But whether a native stone is of igneous or of metamorphic origin appears to be a matter of little interest. At one time, when the technique of this really marvellous process had not been fully developed, it was possible to detect artificially produced stones by the presence in them of round bubbles and curved striæ. But now these can be avoided, and the boot is rather on the other foot. It is easier to detect a native stone by its imperfec-

tions and lack of uniformity. Internal striæ, silk, or bands of colour are here arranged in straight lines at angles of 60° or 120° ; and any cavities have angular boundaries. The reason for this is that the crystals have grown extremely slowly and have been able to develop their proper external crystal faces; and further, during the long period of growth conditions have not always remained the same. It would be possible to write a whole book on the imperfections of crystals, both natural and artificial. Compare, for example, the crystals of ruby represented in fig. 45 and Plate V. Artificially produced crystals have grown relatively quickly under quite uniform conditions. The laws of crystallization have not been changed. The only real difference is in the introduction of the element of time. We have just been doing the same thing more quickly.

KEY TO THE CHARACTERS OF CORUNDUM

Crystals, rhombohedral, $\alpha = 57^\circ 34'$. Composition, alumina, Al_2O_3 . Specific gravity, 4.0. Hardness, 9. Optically uniaxial, negative. Refractive indices, ϵ 1.760, ω 1.768. Colourless or variously coloured. Dichroism varying with the colour. Varieties: ruby (red), sapphire (blue), emery (black). Localities: Burma, Ceylon, Siam, Kashmir, &c.

CHAPTER XIV

Spinel and Chrysoberyl

THESE two mineral species are listed together as aluminates in the table of chemical compositions (p. 73), and they have about equal rank as precious stones. They are sometimes classified with the oxides, being regarded as double oxides of aluminium with magnesium or beryllium; but otherwise there is no relationship between them, and in the forms of their crystals they are quite distinct.

SPINEL is a member of an important group of minerals known as the spinel group, all of which crystallize in the cubic system, and almost invariably in the form of the simple octahedron (fig. 4, p. 32). The general chemical formula for all members of the group may be written as $MO.R_2O_3$ or MR_2O_4 , where M stands for magnesium, ferrous iron, manganese, or zinc, and R for aluminium, ferric iron, manganese, or chromium. Such an assortment can yield quite a wide range of minerals. When both M and R are iron we have Fe_3O_4 or magnetite, an important ore of iron, and also well known as lodestone, which in the old books was mentioned with the precious stones. $FeCr_2O_4$, chromite, is the principal ore of chromium; and $ZnAl_2O_4$, zinc-spinel or gahnite, is one of the rarer ores of zinc. Gahnite is usually of a deep green colour, and quite likely it may some day be found as material of gem quality.

Spinel proper is magnesia-spinel with the formula $MgO.Al_2O_3$ or $MgAl_2O_4$, but small amounts of iron and chromium are usually present replacing mag-

nesium and aluminium. These minor constituents provide the colouring matter, colourless spinel being quite a rarity. With increasing amount of iron the mineral grades into the black opaque variety known as ceylonite, which is found with the gem spinel in Ceylon and has occasionally been cut as a black stone.

Clear spinel of gem quality may show a wide range of colours—crimson, pink, yellow, brown, green, blue, purple, violet, &c., of various shades. A good series of coloured spinels is exhibited in the Birmingham Art Gallery. The spinel found with ruby in Ceylon and Burma is often of a ruby-red colour and is often incorrectly called "ruby-spinel" or "spinel-ruby", both names really meaning a ruby-red spinel, for there is no relationship between ruby and spinel.

Some other vague and misleading names have been given to colour varieties of spinel; these are better suppressed, but one may be mentioned on account of its interesting history. The name "balas-ruby" is often applied to pale red spinel of inferior quality. Red spinel has long been known to occur with ruby in white marble near Jagdalak in Badakshan, the ancient kingdom of Balascia, now in Afghanistan. The old mines were visited by Marco Polo in the thirteenth century and he brought back gem-stones (no doubt both ruby and red spinel) under the name *balascus*. Camillus Leonardus in 1502 writes:

Balasius, is of a purple or rosy Colour, flames and glitters. . . . Some think it is the *Carbuncle* [i.e. ruby] diminish'd in its Colour and Virtue; just as the Virtue of the Female differs from that of the Male. It is often found that the external Part of one and the same Stone appears a *Balasius*, and the internal a *Carbuncle*, from whence comes the Saying, that the *Balasius* is the *Carbuncle's* House. . . . It gives help to Disorders of the Liver; and, what is still more surprizing, if you touch the four Corners of a House, Garden, or Vineyard, with the *Balasius*, it will preserve them from Lightning, Tempest and Worms.

Spinel is usually found as single isolated crystals or as water-worn grains, rarely as aggregates or clusters of crystals; and the octahedral form is often developed with model-like regularity. They are usually quite small, $\frac{1}{8}$ or $\frac{1}{4}$ inch across, crystals up to 2 inches across being rare. Twinning is very frequent, two octahedra having grown, as it were, back to back in symmetrical position (fig. 38, p. 115). This type of twinning is met with in some other cubic minerals, but it is so typical of spinel that it is called the spinel twin-law.

Being cubic, spinel is optically isotropic and not pleochroic, and these characters alone will not distinguish it from glass or the garnets. It is readily distinguished from these by its superior hardness; and crystals of garnet very rarely show the form of the octahedron.

As found in nature spinel is a constant companion of corundum. It occurs in the same rocks and has been formed under the same conditions (p. 153), but in the presence of some magnesia to combine with the alumina. Gem spinel is collected from gravels in Ceylon, Burma, Siam, and Australia.

A noteworthy specimen of spinel is the "Black Prince's ruby", now in the imperial state crown of the British regalia, and said to have been worn by Edward, Prince of Wales, at the battle of Crécy in the year 1346. It is a polished pebble still showing indications of the original octahedral form. Two large polished crystals of red spinel of the same type are exhibited in the British Museum collection of minerals; these were taken from the Emperor of China's Summer Palace in 1861.

Spinel of fine gem quality and with a wide range of rich colours, or perfectly colourless, has been manufactured in large amounts during recent years by the Verneuil process (p. 102). This manufacture has led to some very interesting and unexpected results. In the early experimental work, to obtain a blue colour in the artificial corundum, cobalt was naturally first tried,

but it was found that to obtain this colour with cobalt magnesia must also be added to the mixture. The product was at first thought to be sapphire, but it was afterwards found to be really spinel. Some of this spinel is of an entirely new type, differing from any spinel yet known in nature. It was found to contain an excess of alumina over that required by the spinel formula $\text{MgO} \cdot \text{Al}_2\text{O}_3$; and this excess may be present in gradually varying amounts up to $\text{MgO} \cdot 5\text{Al}_2\text{O}_3$, that is, five molecules of alumina with only one of magnesia. This curious anomaly presented quite a problem, which was only finally solved by the X-ray method of examining crystals. By this method it has been proved that alumina does not always crystallize in the rhombohedral system as the common mineral corundum, but that under certain conditions it may also crystallize in the cubic system. It can also crystallize in the hexagonal system; and there is not one alumina, but three aluminas. The rhombohedral form is distinguished as α -alumina and the cubic form as γ -alumina. Now the crystal-structure of γ -alumina shows a close relation to that of spinel, and the two are capable of growing together to form a single individual crystal, known as "mixed crystal" (p. 71). The γ -alumina is an unstable form at ordinary temperatures and pressures, and for this reason it is not found as a natural mineral, though it no doubt exists deep down in the earth's crust. In the mixed crystals it is held in control by the spinel. But when such a crystal is tempered for some hours at 800°C ., the excess of alumina begins to fall out from the solid solution as α -alumina, and the stone then shows a moonstone sheen and asterism. Tempered for longer periods, more α -alumina separates and the stones become opaque.

A similar phenomenon is met with in the gem mineral fibrolite, the artificially produced crystals of which usually contain an excess of alumina. Such crystals of

fibrolite may be seen when thin sections of porcelain are examined under the polarizing microscope.

CHRYSOBERYL is an ancient name meaning yellow beryl (*χρυσός*, gold), which, like chrysolite, must have been applied to a variety of different stones. The mineral now known by this name was first recognized as a distinct species by A. G. Werner in 1789, before the discovery of the chemical element beryllium, which is an essential constituent of the mineral. It is an aluminate of beryllium, or a compound of the oxides of aluminium and beryllium, $\text{BeO} \cdot \text{Al}_2\text{O}_3$ or BeAl_2O_4 .

With a hardness of $8\frac{1}{2}$ on the scale, chrysoberyl comes next to corundum and diamond, and until quite recently it was the third hardest of all known minerals. The new mineral bromellite, consisting of beryllium oxide, BeO , and with a hardness of 9, has been formed in Sweden as a few small crystals; and it may turn up some day as a gem-stone.

Crystals of chrysoberyl are orthorhombic and they show a strange likeness to crystals of its namesake chrysolite (= olivine). Fig. 48*a* of a simple crystal of chrysoberyl represents equally well a crystal of olivine, the very slight difference in the angles not being appreciable in the drawing. In chrysoberyl the angle between the normal to the faces *a* and *s*, $as = 46^\circ 46'$, and $bi = 59^\circ 53'$; the corresponding angles in olivine being $47^\circ 2'$ and $59^\circ 36\frac{1}{2}'$, scarcely enough to distinguish the two crystals unless accurate measurements can be made. There must be some reason for this, and also for the strange fact that while crystals of chrysoberyl are almost always twinned, those of olivine are very rarely twinned. It will be noticed that the angle *bi* is very nearly 60° , as between the prism faces of a hexagonal crystal (e.g. beryl). Between the planes *b* and *i* there is a possible plane at $29^\circ 53'$ to *b*; and twinning on this plane gives rise to pseudo-hexagonal forms

(fig. 48*c*), which is a very characteristic feature of chrysoberyl. In fig. 48*b* the second crystal is brought into position by a reflection of the first crystal across the twin-plane, or by a rotation anti-clockwise through an angle of $59^{\circ} 46'$ ($= 2 \times 29^{\circ} 53'$) about an axis perpendicular to the face *a*. In fig. 48*c* the third crystal is brought into position by a similar rotation in the opposite direction. The three crystals are then grown together with interpenetration. The face *a* is grooved or striated parallel to its intersection with the prism or striated parallel to its intersection with the prism

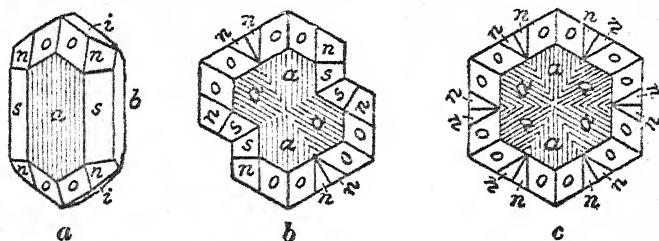


Fig. 48.—Crystals of Chrysoberyl.
(a) Simple crystal. (b) Twinned crystal. (c) Triplet

face *s*, and this gives the V-shaped markings to be seen on nearly all crystals of chrysoberyl. Many crystals usually have the form of quite thin plates parallel to *a* and with a hexagonal or triangular outline.

The colour of chrysoberyl is usually pale yellow, brown, or green. Perfectly clear and colourless crystals have recently been found in the ruby mines at Mogok in Upper Burma and in the Gold Coast in West Africa. Ruby-red and sapphire-blue crystals are not known, but there is no reason why they should not one day be found. An interesting colour variety of chrysoberyl is called alexandrite. This shows a dark green colour by daylight and a deep red by artificial light, best seen in faceted stones that have been cut with the table facet parallel to the face *a* of the crystal. The crystal is strongly pleochroic, and a ray of white light

passing through this face emerges as a red α -ray and a green γ -ray (see fig. 21, p. 54). Further, the spectrum of white light passing through this face shows strong absorption bands in the yellow and blue. In daylight, which is richer in blue rays, the predominating colour will then be green; whilst in lamplight, which is richer in red and yellow rays, the predominating colour is red.

Another interesting optical phenomenon is shown by the cat's-eye variety of chrysoberyl. A cabochon stone cut with its base parallel to the vertical axis of the crystal (any plane parallel to the edge between the faces a and s in fig. 48 *a*) shows a silvery band of reflected light, which, as the stone is moved about, moves over the surface. This is due to the presence in the crystal of vast numbers (25,000 per square centimetre) of excessively minute hollow channels parallel to the vertical axis. This "chatoyancy" is an accidental character and may be shown by any mineral possessing a finely fibrous structure, with parallel fibres in one direction, e.g. quartz, tourmaline, asbestos, and even a reel of silk. Chrysoberyl cat's-eye is often called cymophane, a name given by R. J. Haüy in 1797, from $\kappa\upsilon\mu\alpha$, a wave, and still used by French mineralogists as the name for the species chrysoberyl rather than as a variety name (*œil-de-chat*). The different kinds of cat's-eye are best distinguished by prefixing the name of the mineral, as quartz cat's-eye, &c.

Chrysoberyl occurs in pegmatite, granite, gneiss, and mica-schist. Flat crystals are found in granite at several places in the New England states of North America and in Moravia. With emerald and phenakite it occurs in mica-schist on the Tokovaya stream north-east of Ekaterinburg in the Ural Mountains; here as the alexandrite variety, named after the Czar of Russia. Most of the gem quality material, including alexandrite and cat's-eye, now comes from Ceylon, but it is known there only as water-worn pebbles in the

alluvial deposits. Pebbles of gem quality are also found in Brazil.

The mineral has been prepared artificially, but only as minute crystals. The so-called "synthetic alexandrite" is a fraudulent substitution of artificial corundum or spinel coloured with vanadium oxide.

KEY TO THE CHARACTERS OF SPINEL

Crystals, cubic, as octahedra; octahedral angle, $70^{\circ} 32'$. Composition, MgAl_2O_4 . Specific gravity, 3.6–3.7. Hardness, 8. Optically isotropic and not pleochroic. Refractive index, 1.72–1.75. Variously coloured, rarely colourless. Varieties: ceylonite, gahnospinel (blue, containing ZnO 18.2%, sp. gr. 3.97, n 1.747). Localities: Ceylon, Burma, Siam, &c.

KEY TO THE CHARACTERS OF CHRYSOBERYL

Crystals, orthorhombic (angles $as = 46^{\circ} 46'$, $bi = 59^{\circ} 53'$). Composition, BeAl_2O_4 . Specific gravity, 3.7. Hardness, $8\frac{1}{2}$. Optically biaxial and positive; strongly pleochroic. Refractive indices, 1.76 and 1.75. Variously coloured, yellow, brown, green; rarely colourless. Varieties: alexandrite, cat's-eye. Localities: Ceylon, Brazil, Urals.

CHAPTER XV

Beryl and Topaz

IN the last chapter we dealt with two aluminates; here we have two alumino-silicates, of about equal rank as precious stones. There are several other alumino-silicates to be mentioned later on. The grass-green colour variety of beryl known as emerald is highly prized as a gem-stone because of its rich colour and the rarity of fine quality material; but it is rather lower both in hardness and in refractive index than topaz. Green topaz is still rarer, but this has not yet been found of a rich emerald-green colour. Supposing that an explorer in, say, Greenland came across a whole mountain of emerald-green topaz, it would be interesting to speculate what would be the reaction of emerald merchants.

Both beryl and topaz are ancient names that were applied to a variety of stones, and it was only at the end of the eighteenth century that they were definitely limited to the mineral species we now know by these names. The chemical element beryllium (or glucinum, so named because of the sweet taste of its salts) was not discovered until 1798 and the metal itself was not isolated until 1828. It was first detected in the mineral beryl of which it is an essential constituent. Beryllium is a difficult element to detect chemically, and it is still more difficult to extract in the metallic state. It is an extraordinarily light, yet hard and silver-white, metal, with a specific gravity of only 1.93. Alloyed with aluminium it gives a hard, strong, and light material

suitable for the construction of aeroplanes and airships. When the process for its extraction can be simplified there will be a greater demand for beryl as an ore of beryllium than for ornamental purposes.

BERYL.—The chemical formula of beryl, given in the textbooks as $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$, is only approximately correct. Analyses usually show the presence of small amounts of water and the alkali metals lithium, sodium, potassium, caesium, and rubidium. The variety caesium-beryl (which is usually pink and includes the colour variety morganite) contains up to 4.56% of caesium oxide Cs_2O .

Beryl crystallizes in the hexagonal system, usually as well-shaped hexagonal prisms terminated by the basal planes (fig. 15, p. 37). Frequently only one basal plane is to be seen, since the crystals have grown attached at one end to the matrix. The prism faces are always striated parallel to their length, that is, to the vertical axis of the crystal. This affords an easy means of distinguishing a crystal of beryl from one of quartz, which also forms hexagonal prisms, but here the prism faces are striated perpendicular to their length. In beryl this striation and grooving may be so pronounced that the crystal has the form of a cylinder and the hexagonal form is quite obscured. This is due to the presence of a second hexagonal prism set at 30° to the first (one face *a* of such a prism is shown in fig. 49*b*) and a repeated alternation of the two sets of faces. In most cases the habit of the crystals is long-prismatic; but in some crystals, particularly of caesium-beryl, the habit is tabular, the prism faces being short, and the basal planes then become the predominating pair of faces. In addition to the prism and basal plane (lettered *m* and *c* in fig. 49), there may also be a series of smaller faces on the edges and corners. These are hexagonal pyramids, one series (*p*, *u*) of which replaces the edges *c/m*, and another series (*s*, &c.) replaces the corners. Occasionally there

may be another series of faces replacing the edges *m/s* (narrow unlettered faces in fig. 49); these are dihexagonal pyramids, with twelve faces above and

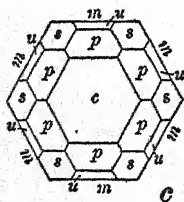
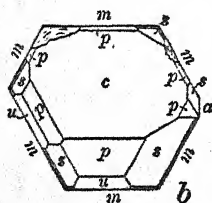
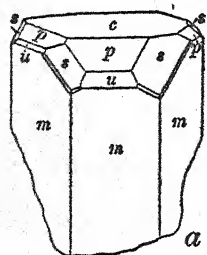


Fig. 49.—Crystal of Beryl (aquamarine) from Brazil

(a) Outline drawing of the crystal shown in Plate VI. (b) Plan of same. (c) Plan showing ideal development of the faces.

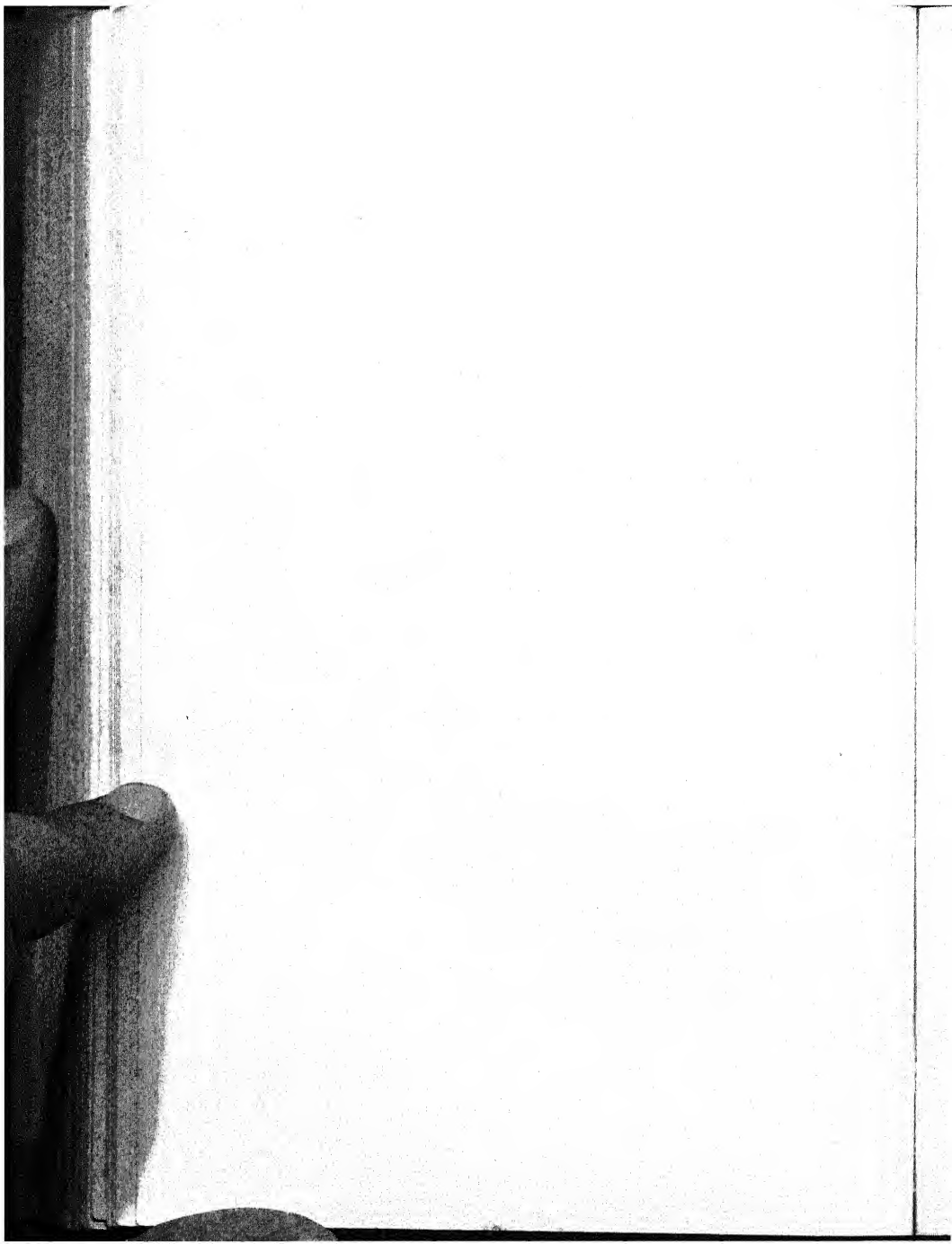
twelve below. The hexagonal pyramid *p* is taken as the unit pyramid, and is inclined to the basal plane at an angle $cp = 29^\circ 56\frac{1}{2}'$, which is the crystallographic constant for beryl and from it all the other angles on the crystal can be calculated. The angle of 60° between the normals of adjacent prism faces is the same for all hexagonal and rhombohedral crystals (corundum, quartz, &c.); but a measurement of the angle *cp* or *cs* at once enables us to determine this crystal as beryl.

The fine crystal of beryl (aquamarine) represented in Plate VI is clear and of gem quality, with a bluish-green colour (a colour which changes to deep blue on heating) and weighs 2505 grams. It affords a good illustration of the actual development of crystals. In the plan (fig. 49*b*) only five *s* faces and only two *u* faces of the six required for a hexagonal pyramid are present; and the corresponding faces differ considerably in size. This is due to accidents of growth, more material having been supplied on one side than on another during the growth of the crystal. If the smaller faces were planed down parallel to themselves the ideal form shown in fig. 49*c* would result. It will be noticed that in figs *b* and *c* all edges between corresponding faces are strictly parallel. The arrangement of the



CRYSTAL OF BERYL (AQUAMARINE) FROM BRAZIL

(Compare text, fig. 49. $\frac{2}{3}$ actual size)



faces on a crystal in zones with a series of parallel edges is an important point to bear in mind. In fig. *c*, for example, there are only three sets of parallel lines (additional ones in fig. 49 *b* are due to intersections between the planes *c* and *s*).

Common beryl is dull and opaque, and usually pale greenish or yellowish in colour. Clear gem varieties show a wide range of colours or may be quite colourless. Crystals of a vivid grass-green colour are the well-known emerald; paler greens, yellowish green, bluish green to deep blue are classed as aquamarine. Golden yellow beryl has been called heliodor; and the pink from California and Madagascar was namedmorganite after John Pierpont Morgan.

Corresponding with variations in the chemical composition there is a range in the specific gravity of beryl from 2.6 to 2.9, the higher values being for the varieties rich in alkalis. Common values are 2.65–2.75. The refractive indices also show some variation, ω 1.57–1.60, ϵ 1.56–1.59. Dichroism is distinct, but not very strong; in emerald the ordinary ray-colour is green and the extraordinary ray bluish green.

Crystals of beryl sometimes attain an enormous size. Plate VII shows a radiating group of large crystals, resembling tree trunks, found in 1928 in a felspar quarry in pegmatite at Albany, Maine, U.S.A. The largest of these measured 18 feet long and 4 feet across, and was estimated to weigh 18 tons. The material was cloudy to opaque and of a pale apple-green colour; but some clear pieces of aquamarine and golden beryl were found. The largest recorded crystal of gem quality is one of aquamarine weighing 243 lb., which was found in pegmatite in Brazil in 1910. The fine crystal represented in Plate VI also came from a pegmatite in Brazil. Material of gem quality has also been obtained from pegmatites in California, Madagascar, South-West Africa, the Ural Mountains, Siberia and elsewhere. Smaller crystals of the same aquamarine varieties are

also found in granite. The best example of a gemstone found in the British Isles is shown by the deep blue beryl from the granite of the Mourne Mountains in County Down, Ireland.

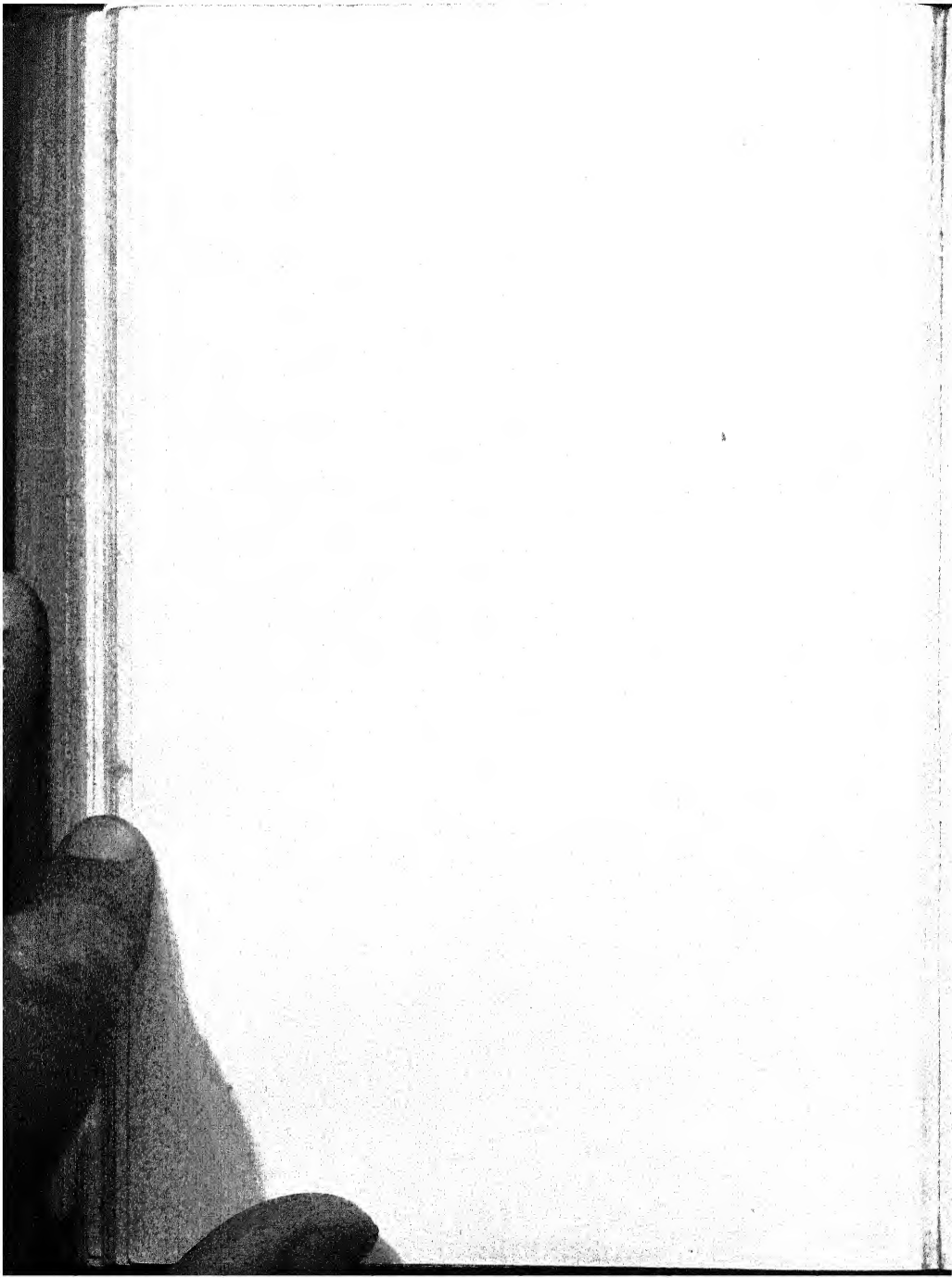
In contrast with the occurrence of aquamarine in rocks of igneous origin, emerald occurs in rocks of metamorphic origin. It has been obtained from mica-schist in the eastern desert of Egypt ("Cleopatra's emerald mines"), on the Tokovaya stream, north-east of Ekaterinburg in the Urals, in the Habach valley in Salzburg, and more recently in northern Transvaal. The famous emeralds from the region around Muzo in Colombia, South America, were mined by the Incas and were seen by the Spanish conquerors in 1537. The mineral is here found in calcite veins in a much folded, black carbonaceous limestone of Cretaceous age, and is believed to be due to metamorphic (pneumatolytic) action from pegmatite veins in the vicinity. A recent discovery of emerald at Bom Jesus das Meiras in Bahia, Brazil, is also in a metamorphic limestone or marble. This occurrence of emerald (as distinct from aquamarine) in metamorphic rocks may perhaps account for the fissures very often shown by these stones; indeed, some jewellers regard a stone with suspicion if it shows none of these flaws.

Small crystals of beryl (including emerald of gem quality) have been produced artificially. So-called "synthetic aquamarine", &c., are fraudulent substitutions of artificial corundum. An emerald glass has been produced by fusing small fragments of crystallized emerald. "Emerald" doublets and triplets are constructed by cementing a thin plate of green glass between quartz or beryl.

In faceted stones beryl and topaz are very similar in appearance and may easily be confused with one another. They have the same vitreous lustre and show very much the same range of colours. They are most easily distinguished by the wide difference in their



LARGE CRYSTALS OF BERYL IN A FELSPAR QUARRY
AT ALBANY, MAINE, U.S.A.



specific gravity; topaz sinks in methylene iodide, while beryl floats. In chemical composition and in crystalline form the two minerals are quite distinct.

TOPAZ is a fluo-silicate of aluminium with the chemical formula $(\text{AlF})_2\text{SiO}_4$. Such a formula corresponds with 20.6% of fluorine, but only rarely is this amount found in topaz. The actual amount may be as low as 15.5%, and then water is also present. This is explained by the partial replacement of fluorine by hydroxyl (OH), and the formula is written $[\text{Al}(\text{F},\text{OH})_2]\text{SiO}_4$. Corresponding with this variation in chemical composition, there is a slight range in specific gravity from 3.52 to 3.57, and in the refractive indices, α 1.61–1.63, γ 1.62–1.64.

Crystals of topaz are orthorhombic with a prismatic development. The prism faces (l , m) are striated parallel to their mutual intersections, i.e. parallel to the vertical axis of the crystal. Other faces shown in fig. 50 are the basal plane c , the unit pyramid u , and the domes f and γ (suggesting the steep roof of *domus*, a house). Variations in the relative sizes of these faces give quite a different appearance to the crystals; but the angles between the faces and the directions of the edges remain the same. Fig. 50 *a* represents the form of crystals from Murzinka in the Urals; and fig. 50 *c* is specially characteristic of the sherry-yellow crystals from Brazil.

An important character of topaz is the perfect cleavage in one direction, parallel to the basal plane. Cracks and feathered flaws due to this cleavage are often to be seen inside the crystals, and these may be rendered more conspicuous by the iridescent colours of thin films. The crystals usually grow attached at one end to the matrix, and when detached they show a smooth and bright cleavage surface at the broken end. The crystals represented in fig. 50 are bounded below

by this perfect cleavage. Double-ended crystals of topaz are rarely seen.

Topaz is usually clear and colourless; but it may be variously coloured, usually in light shades. Pale blue is common; bluish green and green, red and pink are rarer. The popular idea that the characteristic colour of topaz is yellow is quite a myth and needs correction. Crystals of a rich sherry-yellow colour are known only from a single locality in Brazil, namely along the mountain ridge extending from Capão do

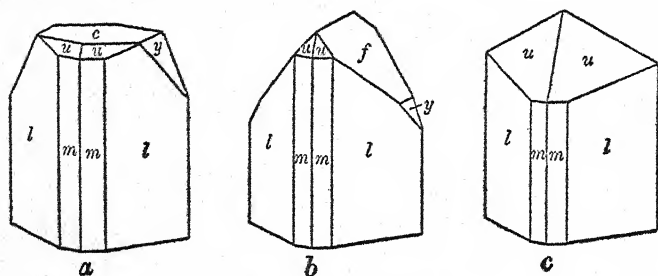


Fig. 50.—Crystals of Topaz
(Terminated below by the basal cleavage)

Lane to Ouro Preto in Minas Geraes. This is often called "Brazilian topaz", but the bulk of topaz from Brazil is colourless or pale blue. Small crystals of a very pale-yellow colour have long been known from Schneckenstein in Saxony. Crystals of a brownish-yellow colour are known from Siberia, Utah, and Colorado; these fade on exposure to light. Books on precious stones, copying one from another, state that yellow topaz is found in Ceylon, a statement that appears to have arisen from the unfortunate confusion in calling the more common yellow corundum "oriental topaz". In Ceylon topaz is found as colourless water-worn pebbles. There is unfortunately much laxity and confusion in the statement of the exact localities of minerals when these are cut as gem-stones. Most of

the material sold as "topaz" is yellow quartz (citrine, "occidental topaz", "Spanish topaz", "Indian topaz", &c.). The Brazilian yellow topaz changes to a bright pink colour when heated ("burnt topaz"). Pink crystals are rarely found with the yellow in Brazil; magenta-coloured crystals are found in gold washings on the Sanarka river in the southern Urals.

Topaz usually occurs in pegmatite and granite and is often accompanied by beryl, crystals of the two minerals being attached to the walls often in same cavity. Another common associate is cassiterite (tin-stone) in veins of tin ore at the margins of granite masses. It is here clearly of pneumatolytic origin. Vapours or solutions of tin fluoride, emanating from the granite magma, by their action on felspar and other rock-forming minerals gave rise to topaz (and other fluorine-bearing minerals, such as fluorite and tourmaline) and cassiterite. Alluvial deposits of stream-tin very frequently contain water-worn pebbles of topaz. Such material, usually colourless or sometimes pale blue, is abundant in the tin mines of Northern Nigeria, Tasmania, and the New England district in New South Wales. Numerous localities could be mentioned for topaz. In the British Isles small colourless crystals occur in the veins of tin ore in Cornwall (too small, however, to be found as pebbles on the beach); with beryl in the granite of the Mourne Mountains in County Down, Ireland, and on Lundy Island in the Bristol Channel; and occasionally as larger pale blue, water-worn crystals in Aberdeenshire. Fine crystals are found in pegmatite veins in the Ural Mountains and in eastern Siberia. One locality in Transbaikalia, where crystals up to 31 lb. in weight have been found, rejoices in the name Borshchovochnoi Mountains (Борщовочный хребет). The British Museum collection of minerals contains a rough opaque crystal weighing 137 lb. from a felspar quarry in Setersdalen, Norway; and a clear, colourless, water-

worn crystal weighing 29 lb. from Brazil. Another clear and colourless pebble, weighing 13 lb., was used years ago as a door-stop in a teashop in Fleet Street, London, and was no doubt thought to be a lump of glass until some bright mineralogist noticed on it the perfect cleavage of topaz.

KEY TO THE CHARACTERS OF BERYL

Crystals, hexagonal; prismatic (rarely tabular) habit; $cp = 29^\circ 56\frac{1}{2}'$. Composition, approximately $Be_3Al_2Si_6O_{18}$, but containing some water and alkali metals. Specific gravity, 2.6-2.9. Hardness, $7\frac{3}{4}$. Optically uniaxial, negative; dichroic. Refractive indices, 1.56-1.59 and 1.57-1.60. Colourless or variously coloured. Varieties: emerald, aquamarine, heliodor, morganite. Localities: Brazil, Colombia, Madagascar, Russia, Siberia, &c.

KEY TO THE CHARACTERS OF TOPAZ

Crystals, orthorhombic; prismatic habit; perfect basal cleavage; $cf = 43^\circ 39'$, $mm = 55^\circ 43'$. Composition, $[Al(F,OH)_2]SiO_4$. Specific gravity, 3.5-3.6. Hardness, 8. Optically biaxial, positive; pleochroic. Refractive indices, 1.61-1.63 and 1.62-1.64. Colourless or variously coloured. Localities: Brazil, Russia, Siberia, Northern Nigeria, &c.

CHAPTER XVI

The Garnet and Tourmaline Groups

THE GARNETS form an interesting and important group of rock-forming minerals. With their bright colours and lustre they would be more appreciated as gem-stones if they were not so common (and consequently cheap). They afford an excellent example of isomorphous mixtures in minerals. The general formula of all garnets may be written $M_3R_2Si_3O_{12}$, where M stands for the bivalent metals, calcium, magnesium, ferrous iron, or manganese; and R for the trivalent metals, aluminium, ferric iron, chromium, or manganese. With these components we can build up quite a number of compounds, the more important of which are as follows:

Calcium-aluminium-garnet	..	$Ca_3Al_2Si_3O_{12}$	..	Grossular
Iron-aluminium-garnet ..	..	$Fe_3Al_2Si_3O_{12}$	..	Almandine
Magnesium-aluminium-garnet ..	..	$Mg_3Al_2Si_3O_{12}$	..	Pyrope
Manganese-aluminium-garnet ..	..	$Mn_3Al_2Si_3O_{12}$	..	Spessartine
Calcium-iron-garnet ..	..	$Ca_3Fe_2Si_3O_{12}$	..	Andradite
Calcium-chromium-garnet ..	..	$Ca_3Cr_2Si_3O_{12}$	..	Uvarovite

Only exceptionally, however, does the composition of a garnet correspond with these simple formulæ. When analysed they are found to be a mixture in indefinite proportions of two or more (or even all) of these molecules. Grossular is rarely found as colourless crystals, and its composition can then be represented by the formula $Ca_3Al_2Si_3O_{12}$; but more often it is coloured owing to the presence of the $Fe_3Al_2Si_3O_{12}$ molecule, and

as this increases in amount we find a passage to hessonite (cinnamon-stone), and finally grading to almandine, where there will also be an intrusion of $Mg_3Al_2Si_3O_{12}$, &c. All these compounds have the same crystalline form, that is, they are isomorphous (*ἴσος*, equal, *μορφή*, form). In the garnet structure the place of M or R can be occupied by any one of the equivalent elements.

The English name garnet is a variant of the older form granate or grenat, still in use in other European languages. T. Nicols (1652) writes:

The *Granats* are kinds of *Carbuncles*: It is a pellucide, red, pretious gemm, like unto the flowers of *Pomegranats*.

Crystals of garnet are cubic with the form of the rhombic-dodecahedron or the icositetrahedron, or combinations of these (fig. 51). Faces of the octahedron or cube are very rarely present. The rhombic-dodecahedron is bounded by twelve rhomb-shaped faces, and the icositetrahedron by twenty-four trapezoidal faces. The icositetrahedron (Greek, *icositetra*, twenty-four, and *hedra*, seat or base) is not to be confused with the tetrahedron; it is also called the trapezohedron. These two simple forms possess the full degree of symmetry of the cubic system (p. 32), and the relation between them is illustrated in fig. 51 *a-d*. By truncating the twenty-four edges of the rhombic-dodecahedron we have a combination of this form with the icositetrahedron; and when this proceeds as far as the total elimination of the *d* faces, we have the simple icositetrahedron. Or by replacing twelve corners of the icositetrahedron we pass back to the rhombic-dodecahedron. Crystals of garnet of these forms have grown embedded in the mother-rock, and they are equably developed on all sides, often with model-like regularity. At times crystals may be closely crowded together, forming a crust on a rock surface in a crevice. When the whole rock consists of garnet (garnet-rock) we have a granular aggregate

of crystals that have interfered with each other's development.

Garnets are typically minerals of metamorphic origin, but they also occur in igneous rocks of various kinds and in mineral veins. When an impure limestone is slowly baked under pressure by a large intruded mass of igneous magma, the alumina and silica of the clayey impurities combine with the lime of the limestone to form a calcium-aluminium garnet. If the impurity is rich in iron (limonite) then a calcium-iron-garnet will result.

Being a cubic mineral, garnet should normally be optically isotropic; but it frequently shows feeble birefringence. This is due to strain and a

zonal structure of the crystals, the several zones or layers being of different chemical composition. A crystal may have started its growth as grossular, but with changing conditions of feed, successive layers may be richer and richer in iron until it finishes off as almandine. With these variations in chemical composition there is no sharp line between different kinds or species of garnet; and, indeed, it is not always an easy matter to distinguish the different kinds, which grade into one another.

GROSSULAR, or gooseberry-stone, is so called because of the pale-green colour shown by some specimens,

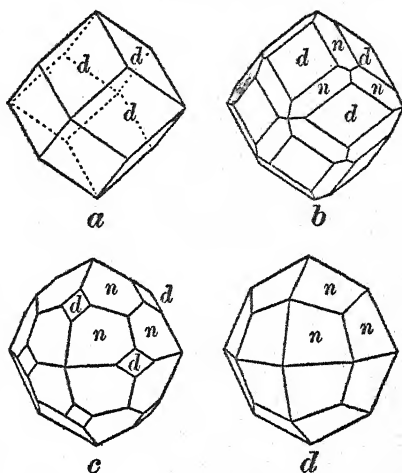


Fig. 51.—Crystals of Garnet

(a) Rhombic-dodecahedron. (b) and (c) Combinations of rhombic-dodecahedron and icositetrahedron. (d) Icositetrahedron.

from *Ribes grossularium*, the gooseberry. Even in quite colourless crystals some iron is present, and as this increases in amount the colour grades to pale green or yellow, reddish yellow or brown. The gem variety *hessonite* or cinnamon-stone of a warm reddish-yellow colour contains 3-4% of iron oxide. The best of this material comes from Ceylon, and smaller crystals are found in Piedmont, the Urals, California, &c. A pale rose-pink grossular as crystals embedded in white marble from Xalostoc, Morelos, Mexico, has been called xalostocite. A compact garnet-rock, closely resembling jade in appearance, has recently been found in the Transvaal, and has been sold as "South African jade". Its colour is various shades of green, cream, and pink.

ALMANDINE is the *Carbunculus alabandicus* of Pliny, so named from the locality Alabanda in Asia Minor. It is of a deep rich red colour, often with a tinge of violet. Most of the material is, however, dark and opaque, and is then used as an abrasive, often as a coating on paper or cloth. Almandine shows three characteristic absorption bands in the yellow to green part of the spectrum; these can be easily seen with a pocket spectroscope, and at once distinguish this mineral from red spinel. Stones are sometimes faceted; but more usually they are cut in the hollow cabochon form (fig. 32c, p. 93), these being produced in large quantities at Jaipur and Delhi in India. Almandine is a mineral of wide distribution, occurring usually in mica-schist and gneiss, and also in granite and pegmatite. Material of gem quality is found in India, Ceylon, at Linde in Tanganyika Territory, and many other localities. "Adelaide ruby" from South Australia belongs here.

PYROPE receives its name from *πυρρός*, fiery, on account of its fiery-red colour. It is the best known of the gem garnets, and has been extensively cut in a faceted form, and sold under a variety of names—

"Bohemian garnet", "Cape ruby" from the diamond mines in South Africa, "Elie ruby" from Elie in Fife-shire, "Arizona ruby" and "Colorado ruby" from the United States. Being a magnesium-garnet its home is in rocks rich in magnesium, such as peridotites (olivine-rocks), serpentine, and in the kimberlite of South Africa. Pyrope usually contains 2-4% of chromic oxide, together with 10% or more of iron oxide, and to these it owes its colour. The Bohemian garnet industry, dating back to the fourteenth century, is centred around Měrunice (Meronitz) and Třebivlice (Trebnitz) in the Midland Mountains of northern Bohemia. The mineral is found in clayey sands and gravels which have been derived from the weathering of a volcanic breccia containing blocks of garnet-bearing peridotite. The garnet-bearing ground is dug from pits, sieved, washed, and hand-sorted for the best stones. Those of inferior quality are used for gravelling garden paths. *Rhodolite* is a beautiful rhododendron-pink variety, intermediate in composition between pyrope and almandine, from Cowee Creek, Macon County, North Carolina.

ANDRADITE is a modern (1868) name in honour of the Portuguese mineralogist J. B. d'Andrada. It is a common garnet occurring in rocks of several kinds, but is generally dull and opaque. A striking variety is that known as *demantoid*, on account of its very brilliant lustre. It has a high refractive index of 1.89 and a dispersion greater than that of diamond; a faceted stone consequently flashes brilliant prismatic colours. Unfortunately it is rather soft, the hardness, $6\frac{1}{2}$, being less than that of quartz; and, as quartz is present in all dust, the stone is liable to become scratched and the edges rounded, especially when worn as a ring-stone. It was first found about 1860 as green pebbles in gold-washings on the Bobrovka stream in the Nizhni-Tagilsk district, Urals, and afterwards as nodules in the neighbouring serpentine-rocks. On

account of its yellowish-green colour and its occurrence in serpentine, it was at first thought to be olivine, and this unfortunate mistake (often misspelt olivene) still persists in the trade. Other names for this stone are Bobrovka garnet and "Uralian emerald", but it has no relation to the true emerald (beryl) which is also found in the Urals. Demantoid has recently been found in the asbestos mines in serpentine in the Val Malenco in Lombardy. A clear yellow variety of andradite known as "topazolite" is found with hessonite in bands of garnet-rock in serpentine in the Ala valley in Piedmont.

SPESSARTINE, or manganese-garnet, takes its name from Spessart in Bavaria. When occurring as large masses it has given rise to deposits of manganese ore. Small crystals of gem quality are found in pegmatite in Ceylon, Madagascar, &c., but these are quite rare. The colour is a rich reddish yellow, very much like that of hessonite.

UVAROVITE, or chromium-garnet, was named after the Russian Count S. S. Uvarov (Уваров), and in the mixed French and German transliterations the name shows a wide range in spellings; but here the stone shows no range in colours, being always emerald-green due to chromium. It is found as small crystals with chromite (chrome iron-ore) in serpentine in the Urals, Orford in Quebec, and a few other localities. Larger crystals have recently been found at Outokumpu in eastern Finland.

TOURMALINE is a boro-alumino-silicate of very complex composition, and no satisfactory chemical formula has yet been deduced. An approximate formula is $(\text{Mg, Fe, Mn, Ca, Na, K, Li, H})\text{Al}_3\text{B}_2\text{Si}_4\text{O}_{21}$, with isomorphous replacements of the several elements bracketed together. It has not been possible to define sub-species, as in the case of the garnet; but iron-

tourmaline, magnesio-tourmaline, and lithia-tourmaline might be distinguished if chemical analyses could be made of every crystal. Another set of names is based on colour—achroite for colourless, schorl for black, rubellite for red, and indicolite for indigo-blue. Others again are "Brazilian ruby", "Brazilian emerald", and "Brazilian sapphire". The term "Brazilian emerald" dates back to Joannes de Laet (1647), long before the name tourmaline came into use. The latter

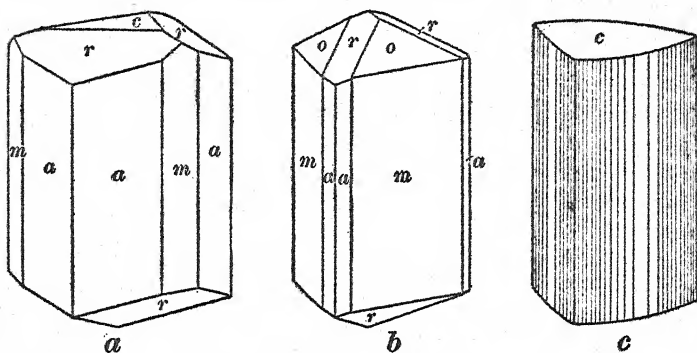


Fig. 52.—Crystals of Tourmaline

is from the Sinhalese name toramalli, which includes also zircon and no doubt other stones. The crystals brought by Dutch merchants from Ceylon in 1703 were found to possess the curious property of attracting warm wood-ashes, and they were then called "aschen-trekker", ash-drawer, or ash-stone.

Crystals of tourmaline are rhombohedral and are remarkable in showing a hemimorphic development of their faces, these being different at the two ends of the crystal, which are usually prismatic in habit. The crystals represented in fig. 52 are bounded by a hexagonal prism *a* and a trigonal (triangular) prism *m*, and terminated by the trigonal pyramids *r* and *o* and the basal plane *c*. The three *r* faces at the top of

the crystal are independent of the three at the bottom (together they would form a rhombohedron, as in fig. 13). The prism faces are always deeply striated and grooved parallel to the vertical axis of the crystal, owing to a step-like repetition and alternation of the faces *a* and *m*. Tourmaline can usually be easily recognized by the very characteristic forms of a curved triangular prism (fig. 52 c), which is seen in no other mineral.

A wide range of colours is shown. Crystals may vary from perfectly clear and colourless to jet-black and opaque; or they may be of various bright colours—red, yellow, brown, green or indigo-blue. Striking differences in colour are often shown in one and the same crystal. A long colourless prism may be tipped with black at one end ("negro-heads"); or a prism may be bright green along half its length, and bright red in the other half; or again, there may be a whole series of different colours along the length of the crystal. In other crystals the zonal arrangement of colours is parallel (instead of perpendicular) to the prism faces, and is then shown on the basal plane. Polished slices cut from the crystal parallel to the basal plane show very effectively the alternating bands of colour, which may be bright green and red.

Tourmaline is remarkable for its very strong dichroism. In darker coloured crystals (especially brown and black) the ordinary ray (vibrating perpendicular to the axis of the crystal) is completely absorbed, whilst the extraordinary ray (vibrating along the axis) is allowed to pass. Such a crystal, when viewed through the prism faces, will show some transmitted light and colour, but when viewed through the basal plane it will be quite opaque. Two thin slices cut parallel to the vertical axis of such a crystal provide a simple polarizing apparatus, well known as the old "tourmaline tongs". When the slices are in parallel position light is allowed to pass through, but when they are in crossed position

the light is cut out. A suitable crystal placed between the crossed slices will show brilliant polarization colours as seen in the polarizing microscope. On account of this strong absorption of the ordinary ray, darker coloured stones should be cut with the table facet parallel to the prism faces, while paler stones will show a better colour when cut with the table parallel to the basal plane.

Another very curious property of tourmaline is its capability of developing a charge of pyro-electricity or of piezo-electricity. The hemimorphic development of the crystals, previously mentioned, is an outward expression of a polarity along the vertical axis. It is easier to go in one direction along this axis in the crystal than in the opposite direction—like uphill and downhill. When a crystal of tourmaline is changing in temperature, either warming or cooling, it develops a charge of positive electricity at one end and a negative charge at the other; it may then attract to itself various light objects, as was early noticed when a crystal was accidentally dropped in warm wood-ashes. This effect may be strikingly shown by the simple experiment of dusting a mixture of red lead and flowers of sulphur through a fine sieve over a cooling crystal, when one end attracts the sulphur and the other the red lead, and they then show yellow and red. When any crystal changes in temperature it also changes very slightly in volume, expanding on heating and contracting on cooling. When pressure is applied in the direction of the polar axis of a crystal of tourmaline (so producing a contraction as with cooling) a charge of "piezo-electricity" is developed. This property has an important technical application in detecting and registering small variations in pressure. In this direction tourmaline is much more useful for depth sounding for submarines than as a precious stone.

Tourmaline is a mineral of wide distribution in igneous and metamorphic rocks of various kinds and

in veins of tin ore. Crystals of gem quality are collected from cavities in pegmatite in Brazil, Madagascar, California, Maine, Urals, &c., and from gem gravels in Ceylon.

KEY TO THE CHARACTERS OF THE GARNET GROUP

Crystals, cubic. Composition, $M_3R_2Si_3O_{12}$. Optically isotropic, sometimes with anomalous birefringence. Rarely colourless; yellow, brown, red, green. Varieties: hessonite, rhodolite, demantoid. Widely distributed.

	M_2R_2	Hardness	Sp. Gr.	Refr. Ind.
Grossular	CaAl	7	3.5-3.6	1.73-1.76
Almandine	FeAl	$7\frac{1}{2}$	4.1-4.3	1.77-1.83
Pyrope*	MgAl	$7\frac{1}{2}$ - $7\frac{1}{2}$	3.7-3.8	1.73-1.75
Spessartine	MnAl	7	4.1-4.3	1.79-1.81
Andradite	CaFe	$6\frac{1}{2}$	3.8-3.9	1.82-1.89
Uvarovite	CaCr	7	3.5-3.7	1.84-1.85

* Pyrope always contains much iron in addition to magnesium; calculated values for pure $Mg_3Al_2Si_3O_{12}$ are sp. gr. 3.510, n 1.705.

KEY TO THE CHARACTERS OF TOURMALINE

Crystals, rhombohedral hemimorphic; $\alpha = 27^\circ 20'$. Composition, a complex boro-alumino-silicate of magnesium, iron, calcium, lithium, &c., with some water and fluorine. Specific gravity, 3.0-3.2. Hardness, 7- $7\frac{1}{2}$. Optically uniaxial, negative; strongly dichroic. Refractive indices, ω 1.64-1.65, ϵ 1.62-1.63. Colourless to black and variously coloured. Varieties: rubellite, indicolite, achroite, schorl. Localities: Brazil, Madagascar, California, Urals, &c.

CHAPTER XVII

Zircon and Olivine

ZIRCON and olivine are the two crystallized gemstones of prime importance left over from the preceding chapters, and they are here dealt with before passing to the non-crystalline opal and the other stones of less importance.

ZIRCON is the mystery stone. The name itself is of obscure origin, and the mineral presents many puzzling and unsolved problems. No other mineral shows such a wide range in its physical properties (density and refractive index); yet no difference in chemical composition and crystalline form can be detected corresponding with these extremes. Further, some crystals when heated undergo remarkable changes in their physical properties and colour. Two chemical elements were first discovered in zircon, namely zirconium in 1789 and the latest found element hafnium.

Other obscure names applied to zircon are jargon or jargoon and hyacinth or jacinth. The Greek name hyacinth was originally applied to blue stones, including sapphire, but now to various reddish-yellow stones, including zircon, garnet, topaz, idocrase and ferruginous quartz (Eisenkiesel). Since this name is also in common use for a well-known plant, it might with advantage be discarded as a gem name.

Zircon is a silicate of zirconium, ZrSiO_4 ; or it may be regarded as a double oxide ZrO_2SiO_2 , since its crystals are isomorphous with cassiterite (SnO_2) and rutile (TiO_2). The crystals are tetragonal with four-

fold symmetry. The square bipyramid p (fig. 53) when present alone resembles a rather flattened octahedron. Usually it is combined with one or other or both of the square prisms m and a , which are set at 45° to one another. In the combination ap (fig. 53 *b*), if the prism faces are shorter, so that the corners of the faces p meet in the middle, the crystal will then closely resemble a rhombic-dodecahedron (fig. 51 *a*, p. 179), and with very nearly the same angles $ap = 60^\circ 40'$ (instead of 60°), while the angle $aa = 90^\circ$ is the same. Such a crystal may easily be mistaken for garnet.

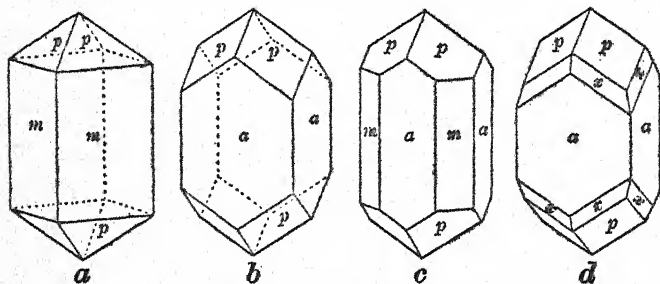


Fig. 53.—Crystals of Zircon

The optical characters of zircon are often anomalous, i.e. not always what they should be for a well-behaved tetragonal crystal. Some crystals are normally uniaxial and show a good uniaxial optic picture (Plate II), but others are either biaxial or isotropic. These three characters may even be shown by different portions of one and the same crystal, with sometimes a separation into distinct zones. The refractive indices show a wide range (1.8 to 2.0), but are always higher than that of corundum and less than that of diamond. Corresponding with this high refractive power, the mineral displays a brilliant lustre, approaching in character the adamantine lustre of diamond. The colouring shows a wide range and is susceptible to changes when exposed to sunlight, heat, X-rays,

radium emanations, &c. Some brown and yellow zircons when heated change to green or bright blue, or they may be completely decolorized. Much of the colourless zircon used as gems has been so treated; with its brilliant lustre and high dispersion it closely resembles diamond in appearance, and is known as "Matura diamond", from Matara in Ceylon. The beautiful sky-blue zircon, which first came into the market in 1914, has probably all been heat treated, but there is much secrecy about the process; and the exact locality in Siam where these stones are found is not made known. Some of these blue zircons very quickly turn brown on exposure to bright sunlight, but the blue colour may be equally quickly restored by slightly warming the stone. Blue zircons do, however, occur naturally: they may have been heat-treated by Nature herself. (Small crystals with a bluish tinge are found in Vesuvian lava.) Some very few rose-red and orange-coloured zircons also show a rapid change in colour to dull greyish-brown on exposure to bright sunlight; one is astonished to see the colour fade away in a few seconds, and equally astonished to see it restored when the stone is warmed. All this is very puzzling and is a matter that requires further study.

Another interesting feature of zircon is seen in the several dark bands in its absorption spectrum. This gives an easy test for the quick identification of the mineral. These absorption bands are due to the presence of minute amounts of uranium and thorium. The presence of these radioactive elements is also shown by the pleochroic haloes commonly seen around microscopic crystals of zircon embedded in biotite mica.

The extreme ranges in specific gravity (4.0-4.7), refractive indices (1.80-1.99), and birefringence (0.01-0.06) shown by clear zircons of gem quality have long presented a puzzling problem. This has now been solved by the new X-ray method of investigation. Those with low values are found to consist, not of the

chemical compound ZrSiO_4 , but of a very fine-grained mechanical mixture of ZrO_2 and SiO_2 . When such a stone is heated to a temperature of 1450°C . the divorced parties may be induced to enter again into chemical union— $\text{ZrO}_2 + \text{SiO}_2 = \text{ZrSiO}_4$ —reaching in some cases, though unhappily not in all, the higher values. This break-down into a “metamict” amorphous state is common enough in many other minerals containing radioactive elements, and is due to the incessant bombardment during millions of years by α -rays emitted at great speed from the slowly disintegrating radioactive elements. That such α -rays actually are emitted by these minerals, including zircon, is shown by their action on a photographic plate in the dark—they can take their own autophotograph. With hydration of the “metamict” material, zircon suffers still further alteration and degradation, becoming dull and opaque with the specific gravity sinking as low as 3.4; then being quite outside the pale of gem-stones. Mineralogical literature is littered with many special names (malacon, cyrtolite, &c.) for such altered zircons.

Zircon is a mineral of wide distribution, but only as minute crystals sparingly disseminated as an accessory constituent in rocks of many different kinds. Only rarely does it occur in large amounts, e.g. in zircon-syenite. The largest crystal on record weighed 15 lb., but this is quite exceptional, few crystals reaching an inch across. Microscopic crystals are to be found in the heavy concentrate of any sample of clay or sand. Being a heavy mineral resistant to weathering agencies, it sometimes accumulates as considerable deposits of a fine zircon sand, which has certain economic uses. Material of gem quality is found as pebbles and water-worn crystals in alluvial deposits, principally in Ceylon, Siam, Queensland, &c.

OLIVINE is an important rock-forming mineral of very wide distribution. It is the main constituent of peridotites, and a pure olivine-rock called dunite forms Mt. Dun in New Zealand. The large masses of serpentine-rocks and the important deposits of chrysotile-asbestos have been derived by the alteration of peridotites. It is also an important constituent of most basalts. In contrast with this abundance of a common mineral, material of gem quality is quite rare.

The name olivine, given by A. G. Werner in 1790 on account of the typical olive-green colour of the mineral, is used by English and German mineralogists for this mineral species. French mineralogists call it peridot, and this name is in common use for the gemstone. But this is not a word of French origin and there is no need to pronounce it as French. There is a prevalent idea that foreign words must be pronounced as French, in the same way that all foreigners are "mon-sieur". The form peridota was in use in English in the thirteenth century, and later peridote, which is a better spelling and conforming with epidote. American mineralogists use the name chrysolite, an old name applied to any yellow stone, from the Greek χρυσός, gold, and λίθος, stone. These three names are now merely synonyms, and it is a matter of choice which is used. Any attempt to limit them to olivine of different shades of colour only means further confusion. The old name chrysolite, so readily confused with chrysotile (= serpentine-asbestos), might now with advantage be allowed to become obsolete.

Olivine is a member of an isomorphous group of minerals ranging from magnesium orthosilicate Mg_2SiO_4 to iron orthosilicate Fe_2SiO_4 , called forsterite and fayalite respectively. Intermediate members containing both magnesium and iron $(\text{Mg,Fe})_2\text{SiO}_4$ are called olivine. With little iron the colour is pale green or yellow, and with more iron it is brown to black. Crystals of a rich green or yellowish-green colour and

of gem quality contain about 10% of ferrous oxide FeO. The crystals are orthorhombic with a form very similar to that of chrysoberyl (fig. 48*a*, p. 165), but they are only rarely twinned. Distinctly developed crystals are, however, rarely found, the mineral being usually as embedded grains of irregular shape. With a hardness of only $6\frac{1}{2}$ (less than that of quartz) faceted olivine must be treated with some care and it is not suitable for wear as ring-stones.

Most of the material of gem quality has been obtained from the small island of St. John's (or Zeberged) off the coast of Egypt in the Red Sea. It occurs there in a vein of nickel ore in altered peridotite, and was formerly collected from the debris on the hillside. Recently a few large crystals of fine quality have come from the Bernardmyo valley near Mogok in Upper Burma. An odd occurrence is in ant-hills in Arizona; bright green grains of olivine, together with red pyrope, both derived from the weathering of peridotite, having been industriously collected by ants. Olivine enters largely into the composition of meteoric stones, and in some masses of meteoric iron clear crystals are large enough to be cut as celestial gems.

KEY TO THE CHARACTERS OF ZIRCON

Crystals, tetragonal; $mp = 47^{\circ} 50'$. Composition, $ZrSiO_4$. Specific gravity, 4.0-4.7. Hardness, $7\frac{1}{2}$. Optically uniaxial, positive, often anomalous, dichroism feeble. Refractive indices, 1.80-1.99; birefringence, 0.01-0.06; dispersion, 0.039. Various colours or colourless. Localities: Ceylon, Siam, &c.

KEY TO THE CHARACTERS OF OLIVINE

Crystals, orthorhombic. Composition, $(Mg,Fe)_2SiO_4$, with about 10% FeO. Specific gravity, 3.3-3.5. Hardness, $6\frac{1}{2}$. Optically biaxial, pleochroism feeble. Refractive indices, 1.65-1.72. Birefringence 0.04. Colour, olive-green or yellowish green. Localities: St. John's Island (Red Sea), Burma, &c.

CHAPTER XVIII

The Quartz Group

NEXT to felspar, quartz is the most abundant of all minerals. The average composition of the rocks of the earth's crust shows 59% of silica, more than sufficient to combine with alumina (15%) and other oxides to make the rock-forming silicates. The excess is present as free silica in the form of quartz, which with its greater hardness and resistance to weathering is really more common and conspicuous than any other mineral on the earth's surface. It also shows a much greater variety in its forms than any other mineral.

The name quartz is an old German mining term mentioned by G. Agricola in 1529. Earlier names in English were "crystal" (from the Greek *κρύσταλλος*, clear ice) and "silex" (Latin).

John de Trevisa in 1398 wrote:

Crystall is a bryght stone and clere wyth watry colour. Men trowe that snowe or yse is made hard in space of many yeres; therfore the Grekys yauē [gave] this name therto.

The poet Robert Greene in 1592 wrote:

The precious stone Silex is full of secret vertue.

Chemically, quartz is silicon dioxide, or silica, and is constant in composition, though it may contain accidentally admixed impurities. It is also constant in its physical properties, the specific gravity varying little from 2.65, and the refractive indices not far from ω 1.544, ϵ 1.553. Crystals are rhombohedral with only axes of symmetry and no planes or centre of

symmetry. Small faces rarely present on the corners of the crystals show a trapezohedral or lop-sided development; and some crystals are right-handed and others are left-handed, one being a mirror reflection of the other. Prominent faces are those of two independent rhombohedra *r* and *z*, which in combination give a hexagonal bipyramid (fig. 54*a*); and the hexagonal prism *m*. When only one rhombohedron is present the crystal has very much the appearance of a cube, the angle *rr* being $85^{\circ} 46'$. Often the faces *r* and *z* at the end of the crystal are different in size, three smaller faces alternating with three larger faces. Quartz, even as minute crystals, can always be recognized by the presence of these faces. The small acute isosceles triangles have plane angles of 70° at the base and 40° at the apex, and the sides are half as long again as the base; alternating with these are larger faces with seven edges (fig. 54*c*). Often, however, the crystals are very irregularly developed and sometimes very puzzling; but they can always be orientated and then deciphered with the help of the horizontal striations which are always shown by the prism faces (fig. 54*d*). Quartz crystals vary enormously in size, from tiny shining specks on a drusy surface up to crystals weighing 1400 lb. They may be aggregated together in various ways, often forming compact aggregates of microscopic crystals and so giving rise to the manifold varieties of this mineral.

The varieties of quartz may well be compared with the varieties of sugar. "Coffee crystals" are single isolated crystals of cane-sugar; these are usually colourless or white, but sometimes they are stained all manner of pretty colours—amethystine, citrine, rose, brown, yellow, red, green, blue. Aggregates of crystals are seen in candy (sugar-spar), which may be colourless, yellow or brown, depending on the degree of refinement of the solution from which the crystals grew. Compact aggregates of smaller crystals interfering with

one another's growth are seen in loaf-sugar. Granulated sugar corresponds to quartz sand; and many other varieties of both sugar and quartz could be mentioned. There is another interesting connexion between quartz and sugar. Polished slices of quartz crystals are used in the construction of saccharimeters for measuring the strength of solutions in the manufacture of sugar and in brewing. This depends on the property possessed by both quartz and sugar of rotating the plane of polarized light.

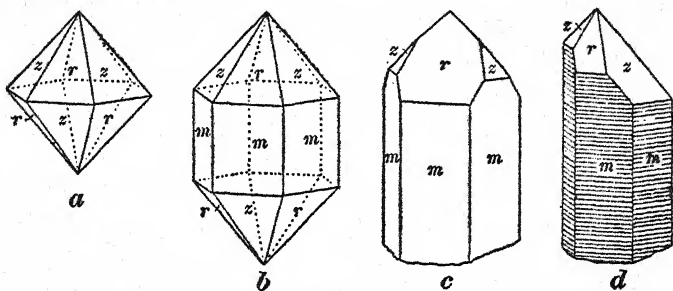


Fig. 54.—Crystals of Quartz

The rotatory polarization of quartz depends on a spiral arrangement along the vertical (triad) axis in the minute structure of the crystal. The crystals are also polar in the direction of the three dyad axes (joining opposite prism edges) and are consequently pyro-electric and piezo-electric in these directions. The use of quartz as resonators and oscillators in radio-telephony and radio-teleggraphy and in the depth sounders for submarines depends on this piezo-electric property.

Quartz is an interesting mineral and it has many important technical applications. But we must not forget to mention its use as a gem-stone. With a hardness of 7 it withstands wear. With the same vitreous lustre and only slightly lower refractive indices, it closely resembles beryl and topaz in appearance; and in cut stones it can only be surely distin-

guished from these by applying the usual tests for specific gravity and refractive index.

The many gem varieties of quartz fall into three groups—transparent, translucent, and opaque. The clear and transparent varieties are single individual crystals and may be either colourless or variously coloured, as in rock-crystal, amethyst, citrine, smoky-quartz, and rose-quartz. These have grown in rock cavities from solutions of silica in hot water under pressure. Translucent varieties consist of an aggregate of needle-shaped crystals of microscopic size with a parallel arrangement in layers. These include the various forms of chalcedony, which again may be colourless or variously coloured, including agate, carnelian, sard, chrysoprase, plasma, &c. Chalcedony was deposited from solution originally as a jelly (a chemical precipitate of hydrated silica), which in the course of time crystallized out as quartz. Opaque varieties consist of a compact finely granular aggregate of minute crystals and coloured with intermixed impurities, as in the variously coloured jaspers. The many varieties of quartz grade so imperceptibly into one another that it is not always easy to give a definite varietal name.

ROCK-CRYSTAL is clear colourless quartz with a bright glassy appearance, and is the purest form of the mineral. It is cut as vases, crystal balls, faceted stones and beads. Large crystals are found in veins in metamorphic rocks and in pegmatite in the Alps and many other places. The main supply of material for optical purposes comes from Brazil ("Brazilian pebble") and Madagascar. Small brilliant crystals have been given the fanciful names "Cornish diamonds", "Irish diamonds", &c. The clear crystals sometimes contain visible enclosures of other minerals. Rock-crystal enclosing fine silky needles and thread-like crystals of rutile is called "Venus's hairstone". Cavities containing liquid with a movable bubble are sometimes present, and when these are extremely minute and present

in vast numbers there is a gradation to milky quartz.

AMETHYST is wine coloured. The Greek word μέθυ for wine is borrowed in the name methyl alcohol (wood-spirit), and methylated spirit is ethyl alcohol (the palatable sort) contaminated with methyl alcohol. In Greek, μέθυστος means soaked with "methu", and ἀμέθυστος (amethustos) means *not* drunken. With such a derivation for the name amethyst, the gem has always been regarded as a charm for the prevention (not the cure) of intoxication. For this reason bishops, whose duties take them to public functions of all sorts, wear an amethyst in the episcopal ring. While indulging in alcohol and the derivation of mineral names, we may perhaps allow still another little lapse. The name alcohol was originally applied to the mineral which we now call stibnite (antimony sulphide). In Arabic الكحل (al-kohl), meaning "the colouring" (*al* being the definite article), is the black powder used to darken the eyelids. This is powdered stibnite, and is still called kohl in the theatrical profession. Gradually the name alcohol came to be applied to any fine impalpable powder, such as can be obtained by distillation; and as late as 1812 Sir Humphry Davy used the term "alcohol of sulphur" for what is now called "flowers of sulphur". An essence or spirit is also obtained by distillation, and so we get to "alcohol of wine" or "spirit of wine", and finally to alcohol.

A fractured surface of amethyst usually shows a series of small ripples suggestive of finger-prints. This is due to a repeated lamellar twinning, but it does not give rise to a parting, as in corundum. Amethyst usually occurs, together with agate, lining the amygdaloidal (almond-shaped) cavities in ancient volcanic rocks, particularly basalt. It also occurs in pegmatite and in mineral veins. At one time it was collected in the amygdaloidal rocks near Oberstein on the Nahe, a tributary of the Rhine, but now the bulk of the material cut at Oberstein comes from similar rocks in the south

of Brazil and northern Uruguay. Material of good quality is occasionally found in the gem gravels of Ceylon.

CITRINE is a clear yellow quartz of various shades from pale honey-yellow to a rich golden yellow. It usually goes in the trade under the name topaz, though, of course, there is no relation between quartz and topaz, and the two are readily distinguished when tested. Supplies come mainly from Goyaz in Brazil and from Madagascar. Some of the yellow quartz sold as "topaz" is "burnt" (i.e. heated) amethyst, but this is of a deeper chestnut-brown colour. With increasing depth of colour citrine grades into:

SMOKY-QUARTZ of a smoky brown or grey colour, and this again grades to *morion*, which is quite black. This is much more frequent than quartz of a good yellow colour. Large water-worn crystals and blocks are found in the streams from the granite mountain of Cairngorm on the borders of Banffshire, Inverness-shire and Aberdeenshire. But the yellow quartz usually passed off as "Cairngorm" or "Scotch topaz" is mainly of Brazilian origin. Here we have a double error, for true topaz of a pale blue colour is also found in the Cairngorm district, and this surely merits the designation of Scotch topaz.

ROSE-QUARTZ is of a pale rose-red or pink colour and very rarely quite clear, being usually only translucent and with an almost greasy lustre and milky appearance. It is found as large masses (up to 8 feet across) in pegmatite at Bodenmais in Bavaria, in the Urals, South-West Africa, Manitoba, Brazil, U.S.A., Madagascar, &c. Crystals are excessively rare (rarer than crystals of diamond!). A very beautiful specimen in the Boston (Mass.) Museum of Natural History shows a wreath of small clear crystals of rose-quartz around a larger prism of smoky-quartz.

PRASE is a leek-green, mostly opaque variety with a greasy lustre. Brighter greens are seen in quartz with enclosed malachite or chrysocolla (copper carbonate

and copper silicate). Blue quartz is rare. Red quartz contains enclosed hæmatite. A crude imitation is made by dropping heated quartz into red ink, when the colour penetrates along cracks.

CAT'S-EYE QUARTZ is a granular aggregate of quartz enclosing parallel fibres of asbestos, or hollow channels if the asbestos has been later removed. When cut in a cabochon form it shows a chatoyant band of reflected light on the surface (compare chrysoberyl, p. 166). "Tiger's-eye" of a golden-yellow colour is of the same character, and is found only in the Asbestos Mountains in Griqualand West in South Africa, but there in large amounts. This is sometimes called crocidolite, but it is really decomposed crocidolite (blue asbestos) replaced by quartz. Associated with it is found "hawk's-eye" of a dark blue colour; here the blue crocidolite was silicified without previous oxidation and decomposition. These South African stones are often stained with aniline dyes, which fade on exposure to light.

AVANTURINE QUARTZ is also a granular quartz or a quartz-schist containing small flakes of mica, which give it a spangled effect. The artificial avanturine is glass containing small bright crystals of copper.

CHALCEDONY forms masses with smooth rounded (mamillated) surfaces and is usually of a white, light grey, or creamy colour with a waxy lustre. It has been deposited from solution as successive concentric layers, and is usually found in the steam cavities in ancient volcanic rocks. It may also be seen lining cavities of hollow flints. Depending on the impurities present in the solution from which it was deposited, the mineral may be variously coloured; or it may have been stained by later percolating solutions. Stones of a yellow, yellowish-red, or red colour, due to iron hydroxide or oxide, are carnelian; brown is sard; bright green, due to nickel, is chrysoprase; dark green, due to chlorite, is plasma; and dark green with red spots is "blood-

stone" or "heliotrope". Other colours are pale blue, violet, and mauve. When the successive layers of the stone are brought into prominence by being differently coloured (due to change in feed during growth), then we have the well-known agate. Here the bands of colour are curved, conforming to the shape of the cavity in which the stone grew. When the bands are straight and alternately black and white we have onyx; or when brown and white, sardonyx. Enclosures of various kinds in chalcedony give moss-agate and mocha-stone.

Since chalcedony consists of an aggregation of minute crystals, the material is slightly porous, the degree of porosity varying in the different layers, and colouring matter in solution can be soaked up between the individual crystals. It is therefore an easy matter to colour chalcedony and agate artificially, and, in fact, most of the agate offered for sale has been so treated, since the bulk of the commercial rough material is very pale in colour. The colour of carnelian can also be easily improved by heating the stone, the yellow iron hydroxide being so converted into the red oxide. The several varieties of chalcedony are common and abundant semi-precious stones.

JASPER consists of a compact aggregate of finely granular quartz mixed with impurities in large amount which act as the colouring matter. There may be a wide range of bright colours, and the material takes a good polish. It is often rather of the nature of a metamorphic rock formed by the baking of mudstone and shale.

KEY TO THE CHARACTERS OF QUARTZ

Crystals, rhombohedral trapezohedral; $\alpha = 85^{\circ} 46'$. Single crystals or aggregates of crystals. Composition, silica, SiO_2 . Specific gravity, 2.65. Hardness, 7. Optically uniaxial, positive; refractive indices, ω 1.544, ϵ 1.553; dichroism feeble. Transparent, translucent, or opaque. Varieties: rock-crystal, amethyst, citrine, chalcedony, agate, carnelian, &c. Localities: ubiquitous.

CHAPTER XIX

Opal and Silica-glass

LIKE quartz, opal consists of silica, but with the addition of water in variable amount, 3-10%. It is a dried-up silica jelly, and is one of the very few minerals that show no trace of crystallization. It is amorphous and optically isotropic (but sometimes birefringent due to strain). In mode of origin and occurrence it is very similar to chalcedony, with which it is often associated as a filling in rock cavities and crevices. But it differs from chalcedony in that the silica jelly dried up without crystallizing. That silica is slightly soluble in hot water under pressure is shown by the extensive deposits of siliceous sinter—a form of opal—from the geysers of Iceland, New Zealand, and the Yellowstone National Park in Wyoming. Opal takes on many other forms. A clear colourless glassy opal called hyalite is found as small spheres in Japan. Opaque common opal includes milk-opal, rose-opal of a fine pink colour, wax-opal with a waxy lustre, wood-opal replacing fossil wood, prase-opal, &c. Fire-opal is transparent with a rich orange-yellow to red colour. This variety comes mostly from Mexico, but it has also been found of good quality in Asia Minor.

PRECIOUS OPAL is distinguished from other varieties by its play of vivid colours, or opalescence. These colours are not in the stone itself and are only to be seen in reflected white light. An opal when viewed by transmitted light, by holding it up in front of a window, shows only a pale yellowish or milky colour. The

prismatic or rainbow colours seen are an optical effect due to the breaking up of white light by interference. The interference is here produced by the reflection of light from the two surfaces of a thin film, the thickness of which is comparable to the wave-lengths of light. The polarization colours of crystals mentioned on p. 51 are also due to interference, but produced in another way. The flashes of prismatic colours shown by diamond are due to quite another cause (p. 46). The vivid colours of thin films are well known in soap-bubbles, blown glass, devitrified Roman glass, oil patches on a wet pavement, iridescent tarnishes on metals and certain minerals, and in feathered cracks and cleavages in crystals. "Newton's rings" from a film of air may usually be seen when the table facet (which is often very slightly curved) of a cut gem is pressed against a sheet of glass. All these are due to the same cause.

A ray AB of light striking the surface of the film at B (fig. 55) is partly reflected and partly refracted along BC . At the second surface part of this ray passes through and part is reflected at C along CD to emerge from the film along DE . Another parallel ray, from the same source, with the same wave-length and with its wave motion in the same phase, strikes the top surface at D and is partly reflected along the same path DE . The two waves travelling along this same path are now opposed in phase, and in their endeavours to vibrate in opposite directions they eliminate one another. If this is the wave-length of red light, then red will be cut out and the complementary colour will be seen. The difference in path between BCD and GD , from the wave-front BG , amounts in the diagram to one whole wave-length; but the same interference will result if the difference amounts to a small number of whole wave-lengths. The length of the difference in path depends on the inclination of the incident ray and on the thickness of the film (and also

on the refractive indices of the two media); and with a difference inclination or thickness other wave-lengths or colours will be cut out. It will be noticed in the diagram that there is a loss of half a wave-length in the reflection at the surface from the lighter and denser media.

The vivid and varied colours shown by precious opal with their arrangement in patches and splashes over the surface of the stone must clearly be due to this interference of light in thin films. Many explanations

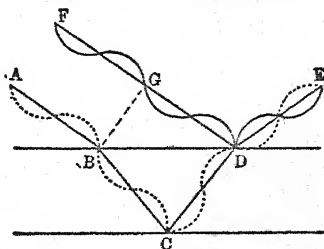


Fig. 55.—Interference of light waves in a thin film

of the nature of these films have been offered, but their true nature still remains unknown. Here is an interesting problem for some keen admirer of opals. The films cannot be open cracks filled with air (or a vacuum), as in the iridescent cracks seen in rock-crystal and the cleavage cracks in topaz, otherwise the stone would surely fall to pieces. A jelly on drying out develops a complex system of cracks, and in opal these may have been filled with a second deposition of silica with a slightly different index of refraction. Hydrophane (*oculus mundi*) is a variety which shows a play of colours only when the stone is immersed in water.

To show the play of colours to the best advantage the stone must be cut with a flat cabochon form and mounted in a closed setting, so that it can be viewed only by reflected light. Thin slices of opal are often mounted on a backing. A dried-up silica jelly is easily obtained by precipitation from a solution of sodium silicate ("water-glass"), but it has not yet been possible to control by artificial means the production of anything resembling precious opal. Fire-opal, being a transparent stone of attractive colour, but without play of colours, is cut in a faceted form.

Opal is a mineral of wide distribution, but it is only at a few localities that precious opal is found. The statement in the old books that it came from India is probably a myth. The opal known to the Romans no doubt came from Hungary, which, until the discovery in 1877 of the much richer Australian deposits, was the only source. This Hungarian locality is now in the province of Slovakia in the new Czechoslovakian Republic. The mines are near Červenica (the more usual spelling Czerwenitz is Polish and German), which in Hungarian was called Vörösvágás, a translation of the Slovak name meaning "red town". Another Slovak village near the opal mines is Dubník, which was called Opálbánya (i.e. opal mine) in Hungarian. Here the opal is found in cavities and crevices in a volcanic rock (andesite) of Tertiary age, and hot springs still exist in the neighbourhood. The ancient mines are now almost abandoned.

In Australia the mode of occurrence is quite different. Here the precious opal is found as thin bands along the bedding planes and as seams in the joint-planes in sandstones and shales of Cretaceous age. The age of the beds is definitely fixed by the fossils they contain, wood, shells, and bones of reptiles being often replaced by precious opal. Small open workings have been made at many places in southern Queensland and in northern New South Wales. In Queensland the rocks are usually hard and dark brown and of the nature of a siliceous ironstone or ferruginous jasper. At White Cliffs and Lightning Ridge in New South Wales the rocks are softer and lighter in colour. The "black opal" from Lightning Ridge shows the play of colours on a dark background. More recently, opals of fine quality have come from Coober Pedy in Stuart Range in the centre of South Australia.

SILICA-GLASS is still another form of silica, similar to opal in being amorphous and optically isotropic, but differing from this in containing no water. This has been discovered only quite recently under very remarkable circumstances, and the origin of the material remains a complete mystery, though clearly it is a fused product. The melting-point of silica (quartz) is very high— $1710^{\circ}\text{C.} = 3110^{\circ}\text{F.}$ —and it is difficult to understand how, where, and when it could have been fused as a natural product. It was found by Mr. P. A. Clayton of the Desert Survey of Egypt when mapping an unexplored region of the Sand Sea in the Libyan Desert, at a spot 300 miles beyond the last water hole and never before visited by man since Palæolithic times. The Libyan Desert beyond the oases of Bahariya, Farafra, and Dakhla is a land of mystery. Here in the Sand Sea was lost the army of 50,000 Persians sent by King Cambyses in 525 B.C. to conquer Libya, and no trace of it has since been found. Somewhere here is perhaps the lost oasis of Zerzura of Arab legends. Range upon range of sand-dunes up to 300 feet in height and with an angle of slope of 30° (1 in 2) on the eastern, leeward sides extend north to south for over 200 miles, forming an impassable belt from east to west 150 miles in width. The district can be approached only from the north where the valleys or "streets" between the high crested dunes are partly filled with "whale-back" dunes; or from the south where the dunes thin out. There is no water, and not a living thing is to be seen in this Sand Sea. The material and accounts brought back by Mr. Clayton were so astonishing and perplexing that I was glad to have the privilege of joining a special expedition of the Survey of Egypt to investigate this remarkable and unique occurrence of the silica-glass.

We—three white men and nine Arabs—started from Cairo on 30th November, 1934, with four Ford motor-cars, fitted with truck bodies and nine-inch tyres,

fully loaded with petrol, water, and camp equipment. A transport of thirty-two camels with 800 gallons of petrol and oil had been sent in advance from rail at Beni Mazar to 'Ain Dalla, the last spring in the desert, 360 miles south-west of Cairo, this double journey taking a month. A dump of water and petrol was made, with double motor-car journeys, still farther into the desert, a hundred miles west of 'Ain Dalla. The position of this dump was carefully fixed to two seconds of arc by star observations for latitude and wireless time signals for longitude, for if it could not be found again or were covered by a sandstorm we should never have returned. Thence we proceeded south-west, steering by compass, but on a zigzag course, charging the high dunes at top speed whenever a passage seemed possible to the pilot car and sliding down the other side—a really alarming but very exhilarating experience. When the cars got stuck in patches of loose sand they had to be hauled out on rope ladders; and in sandstorms we had to seek protection against the cars. The temperature ranged from 33° F. at night to 110° F. at midday. Then, proceeding southwards, we raced along the gravelled "streets" between the high crested dunes, avoiding occasional rocky outcrops of Nubian sandstone. Finally, on 8th December, Camp 7 was pitched in the centre of the silica-glass area at lat. 25° 17' 54" N., long. 25° 34' 0" E., after travelling nearly a thousand miles. Several other camps were pitched in this district, and in the meantime cars went back to the dump for supplies of water and petrol. To pass from one "street" to the next, only a couple of miles away, it was necessary to run to the southern end of the dunes—twenty miles or more down one street and the same distance up the next. The silica-glass was found over an area of 85 miles N.-S. by 35 miles E.-W., but only as wind-worn lumps lying here and there on the surface of the gravelled streets between the dunes. All attempts to trace the

material to any source or to arrive at any idea as to its origin were unfortunately not successful. It might simply have fallen from the sky; but the material is quite different in composition from any meteorites that have been observed to fall. No trace of iron meteorites or of meteorite craters could be found, as at Wabar in Arabia, where the desert sand was melted by the fall of enormous meteorites, giving rise to the legend of the city destroyed by fire from heaven. Silica-glass was also found as fulgurites or lightning-tubes, formed by the fusion of sand when lightning strikes the dunes; but these are only paper-thin tubes and can have no relation to the solid lumps of silica-glass.

This silica-glass from the Libyan Desert is pale greenish yellow in colour and varies from quite clear to cloudy. It was found as irregular lumps, wind-worn by the eroding action of sand blasts, and usually not more than a few ounces in weight. The largest mass found weighed 16 lb. and several hundredweights of the material could have been collected. Specimens are exhibited in the Geological Museum at Cairo and in the mineral collection of the British Museum of Natural History at South Kensington. When cut (Plate VIII), the material has much the appearance of a pale olivine, but it lacks brilliancy owing to the low refractive index (1.4624 for yellow sodium-light). As a gem-stone possibly of celestial origin it appeals to the imagination. A point of special interest is that the material was worked by Palæolithic man; but later it was not known to the ancient Egyptians. Numerous wind-worn flakes of the glass were found together with stone implements, querns, and quartzite flakes. The climate there must have been very different 15,000 years ago to what it is now.

Closely allied to the Libyan Desert silica-glass is the moldavite found on ploughed fields in two restricted areas in southern Bohemia and western Moravia, which, since before 1787, has been cut as a gem-stone under the

names "obsidian" or "water chrysolite". This glass, however, contains only 75-80% of silica as against 98% in the Libyan Desert glass, and containing more iron it shows a deeper green colour. Similar glasses of a dark brown to black colour are found in Australia (australites or "blackfellow's buttons"), Dutch East Indies, Malay, and French Indo-China. They are classed as tektites, and the current theory is that they have fallen from the sky and are of meteoritic origin. Obsidian is a volcanic glass differing in composition from these.

The first atomic bomb exploded in New Mexico in 1945 formed a saucer-shaped crater half a mile in diameter covered with "jade- and turquoise-coloured" silica-glass, produced by the melting, "boiling and bubbling" of the desert sand: but this material can scarcely be of gem quality.

KEY TO THE CHARACTERS OF OPAL

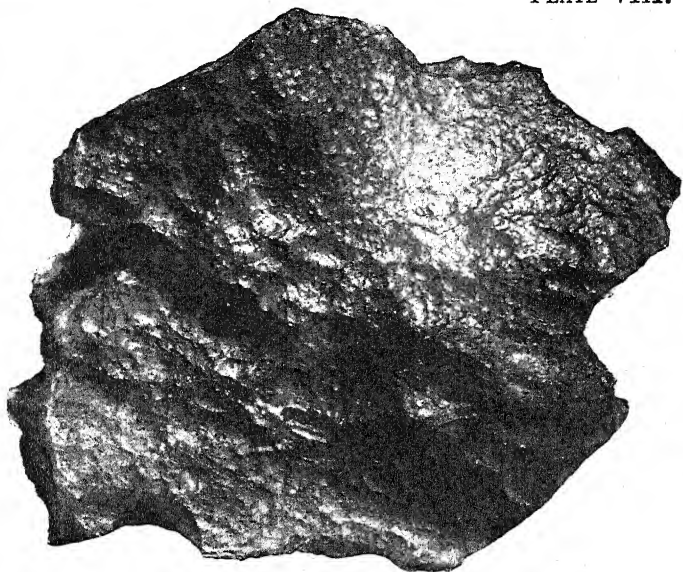
Amorphous. Composition, hydrated silica. Specific gravity, 2.0-2.2. Hardness, $5\frac{1}{2}$ -6 $\frac{1}{2}$. Optically isotropic (sometimes birefringent). Refractive index, 1.40-1.46. Varieties: precious opal, fire-opal, rose-opal, milk-opal, &c. Localities: Australia, Mexico, Czechoslovakia, &c.

KEY TO THE CHARACTERS OF SILICA-GLASS

Amorphous. Composition, silica, SiO_2 , 98%. Specific gravity, 2.21. Hardness, 6. Optically isotropic. Refractive index, 1.46. Colour, pale yellowish green. Locality: Libyan Desert.

KEY TO THE CHARACTERS OF MOLDAVITE

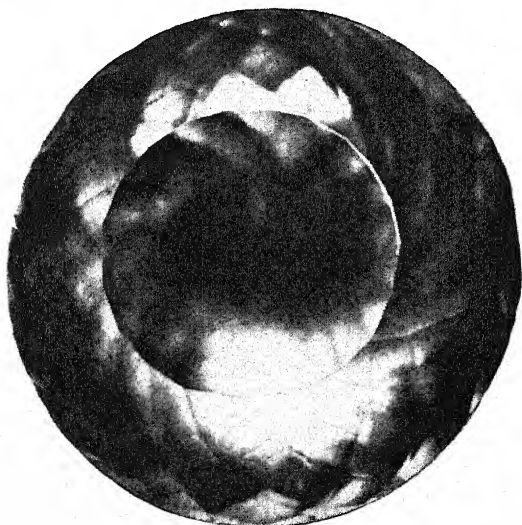
Amorphous. Composition, SiO_2 , 75-80%, with alumina, iron, calcium, &c. Specific gravity, 2.3-2.4. Hardness, $5\frac{1}{2}$. Optically isotropic. Refractive index, 1.48-1.50. Colour, dark green. Localities: Bohemia and Moravia.



SILICA-GLASS FROM THE LIBYAN DESERT

Wind-worn mass weighing 5 lb. $\times \frac{2}{3}$

British Museum



SILICA-GLASS FROM THE LIBYAN DESERT

Faceted gem weighing 806½ carats (actual size)

Author's Collection

Facing p. 208



CHAPTER XX

Jade (Nephrite and Jadeite)

SEVERAL compact minerals of a greenish colour have been, and still are, confused under the term jade, which should now be restricted to the two minerals nephrite and jadeite. The name jade is a corruption of the Spanish "piedra de ijada", or stone of the flank or side, because if worn there it was believed to be a cure for the colic. Another old name with the same idea was "lapis nephriticus", kidney-stone, from which the present name nephrite is derived. Sir Walter Raleigh in *The discoverie of the empyre of Guiana* (1596) wrote:

A kinde of greene stones, which the Spaniards call *Piedras Hijadas*, and we vse for spleene stones.

Nephrite and jadeite are extraordinarily alike in their external appearance, and often they can only be distinguished by an examination of their essential characters. Yet chemically they are very different; nephrite being a silicate of magnesium and calcium with often a little iron, while jadeite is a silicate of sodium and aluminium. Both consist of a compact aggregate of crystals of microscopic size, often intermixed with other minerals, so that they partake rather of the nature of rocks. In thin sections under the polarizing microscope they are at once distinguished, but this is not a practicable method of dealing with a valuable jade ornament. The easiest test is given by the difference in specific gravity, the value for nephrite,

3.0 or up to 3.1 in darker varieties richer in iron, being appreciably lower than that for jadeite, 3.3. It is a comparatively easy matter to weigh even a largish ornament in air and in water for the purpose of determining the specific gravity. The method of determining the refractive index with the refractometer is not available, as the stone is not polished with perfectly flat surfaces. If a minute fragment can be detached, the refractive index can be determined under the microscope.

NEPHRITE is a member of the amphibole group of rock-forming minerals, differing from tremolite and the iron-bearing variety actinolite only in the habit and state of aggregation of its crystals. If the crystals are very long and thin, like hairs, and aggregated in parallel bundles, then we have the well-known asbestos; but if they are short and closely felted and matted together in a solid compact mass, then we have nephrite. It is this peculiarity of structure that accounts for the extreme toughness of nephrite. It is not a really hard mineral by the scratching test (hardness $6\frac{1}{2}$ on the scale), but it is a very difficult matter to break a pebble of nephrite with a blow from a hammer. (Diamond, though very much harder, breaks quite easily compared with nephrite.) The fractured surface is splintery. The stone takes a very good polish, and on the polished surface the lustre is somewhat greasy in character, especially in stones of paler colour. The colour is usually various shades of green, light to dark, and may sometimes be quite white. Other colours, yellow, reddish or bluish, are rare. In the mass it is opaque, but thin carvings display a certain amount of translucency.

Nephrite occurs in schistose rocks, especially in hornblende-schists, and has been formed by intensive rock pressure in areas of mountain building. Large deposits are worked in China and several places in Eastern Turkestan, principally to the south of Yarkand towards the border of Kashmir and in the Kuen-Lun

mountains. It is worked in open quarries by the primitive method of fire-setting which badly fissures the stone, and is collected as angular blocks from glacial debris or as boulders in the streams. Large boulders are found in streams near the graphite mines near Batagol in the Sayan range west of Lake Baikal in Siberia. A polished boulder of a rich green colour for this district is shown in the mineral collection of the British Museum. It weighs 1156 lb. or only just over half a ton. Here we have a striking example of how facts get miscopied and exaggerated in books on precious stones. In the latest German work the weight of this block is given as 2140 kilograms, or well over two tons!

The New Zealand "greenstone" is well known, but this is not to be confused with the greenstone of geologists, which is an elastic field term embracing a variety of rocks. This nephrite is usually of a darker green colour. It is collected as boulders and pebbles at several places in the rivers along the west coast of South Island, and has been much used by the Maoris for stone axes and carving as "tikis", the flat pebbles of the rather schistose material being well adapted for these shapes. It has also been found in situ associated with talc and serpentine rocks, and was formed by metamorphic processes at the time of the building of the New Zealand Alps. Stone implements of nephrite are found in Europe, especially in prehistoric Swiss lake dwellings, but only comparatively recently has the material been found in situ near Jordansmühl in Silesia, in Liguria, and in the Harz Mountains. A large block weighing 4704 lb. of greyish-green nephrite from Silesia is exhibited in the American Museum of Natural History in New York City. The source of the prehistoric carved objects of nephrite (and jadeite) found in Mexico and Central America has also long been an ethnographical problem. A specimen from Guiana (the locality mentioned by Sir Walter Raleigh in 1596),

carved as a curious cylindrical pendant, came to the British Museum in 1753 with the collection of Sir Hans Sloane.

JADEITE is a member of the pyroxene group of rock-forming minerals. This was not recognized as a distinct mineral species until as late as 1868, having previously been included, as it still is in the trade, under the general term jade. A further confusion is introduced when the term jade is limited to nephrite. Besides the differences between jadeite and nephrite in chemical composition, crystalline structure (determinable only in thin sections under the microscope and with X-ray photographs), and optical characters, there is an important difference in the coarser (though still microscopic) structure or texture of the two minerals. Nephrite, we have seen, is a matted aggregate of fibres; whilst jadeite is an aggregate of small grains—a granular aggregate, and in addition to the grains of jadeite there are always present also grains of albite (soda-felspar) and sometimes of diopside. This granular texture is sometimes evident when a polished surface is examined with a magnifying lens. Further, owing to the slight difference in hardness between the jadeite and the felspar, the polished surface usually shows a fine shagreened appearance. The polished surface of jadeite has a rather more greasy appearance than on nephrite, and the mineral shows a wider range of colours. It may be pure white, pale green to emerald-green, pale blue or mauve to lilac, or pink to a deep red; and the different colours often show as splashes in a ground of a paler colour. These colours are highly prized by the Chinese, and jadeite is the more valuable kind of jade. But a serious error is invariably made in the trade in describing this material as Chinese jade. The few asserted occurrences of jadeite in China are extremely doubtful, but this wide region has not yet been properly prospected, though good work is now being done by the new Geological Survey of China. All the

jadeite so extensively carved and used in China has been imported from Upper Burma; and of course many of the Chinese jade carvings are also done in the nephrite from Eastern Turkestan.

Although prehistoric objects of jadeite have been found in Brittany, Switzerland, Egypt, Asia Minor, Mexico, Central America, &c., the mineral is known to occur in situ at very few places, and Upper Burma is the only commercial source of supply. It is here obtained from the Uru valley in the Myitkyina district, where it occurs in dikes of a metamorphosed rock in a country-rock of serpentine. The chief dike is that at Tawmaw, and others have been worked at Meinmaw, Pangmaw, and Namshamaw. Material is also quarried from a boulder conglomerate of Tertiary age, and some is collected as pebbles from the Uru river. The quarries here have been worked for centuries, but more extensively since 1744, the material being taken overland into China; but now it is shipped through Rangoon, and some is cut in Mandalay.

Several other kinds of minerals may form compact aggregates of a greenish colour, and be mistaken and sold for jade. Serpentine (hydrated silicate of magnesium with some iron, $H_4Mg_3Si_2O_9$) does not always show the characteristic mottling and veining, and in the bowenite variety it is very similar to jade in appearance. Another mineral often used for Chinese carvings is agalmatolite (a hydrated silicate of aluminium) or figure-stone, called in Japanese *rōséki*. Both serpentine and agalmatolite are readily scratched when touched with a knife point, and can so be easily distinguished from jade. Still other minerals are grossular garnet ("South African jade", p. 180), idocrase ("Californian jade"), fibrolite, &c.

Much more could be written on jade and the marvellous Chinese carvings; indeed, perhaps the most remarkable book ever produced deals with this subject. It is entitled *Investigations and Studies in Jade* (New

York, 1906), and is descriptive of the Heber R. Bishop collection of jade, which was presented to the Metropolitan Museum of Art in New York. The two folio volumes weigh 125 lb. and were produced regardless of expense, and the numerous coloured plates are veritable works of art. The edition, limited to 100 copies, was distributed to crowned heads and amongst the principal libraries of the world, a dozen copies coming to the British Isles (a copy is to be seen in the art library of the Victoria and Albert Museum at South Kensington).

KEY TO THE CHARACTERS OF NEPHRITE

Crystals, monoclinic, but only as microscopic fibres forming a felted aggregate. Composition, $\text{H}_2\text{Ca}_2\text{Mg}_5(\text{SiO}_3)_8$, with small variable amounts of iron. Specific gravity, 3.0-3.1. Hardness, 6½; extremely tough. Optically biaxial, negative. Refractive indices, 1.60-1.65. Opaque to translucent. Colour, white to green. Localities: Eastern Turkestan, Siberia, New Zealand, &c.

KEY TO THE CHARACTERS OF JADEITE

Crystals, monoclinic, but only as microscopic grains forming a compact aggregate. Composition, $\text{NaAl}(\text{SiO}_3)_2$; usually mixed with albite. Specific gravity, 3.3. Hardness, 6½. Optically biaxial, positive. Refractive indices, 1.65-1.67. Opaque to translucent. Colour, white to green, &c. Locality: Upper Burma.

CHAPTER XXI

Lapis-lazuli and Turquoise

THESE are both opaque stones whose face colour is their fortune, for they are two of the very few gem-stones that really show a colour of their own.

LAPIS-LAZULI (stone of the blue) is the only gem-stone that has retained a mediæval Latin form of its name, no doubt because it was more important as a source of the pigment ultramarine. For this purpose it was worth its weight in gold, and one can well imagine the outcry of the lapis-lazuli merchants when the artificial product was first introduced in 1828. The retention of "lapis" is appropriate, for the stone is not a simple mineral, but a mixture of minerals and is thus really a rock. The essential blue mineral has been called lazurite (also lasurite and lazulite), and there is still much confusion between these names and azurite, which at different times have been applied to different blue minerals. All are derived from the Persian word *lazzward*, meaning blue colour and also applied to the stone. The Greeks used the name *sappheiros*, and *sapphirus* was used by Agricola as late as 1546.

The colour of lazurite is deep blue, and the mineral is occasionally found as well-shaped rhombic-dodecahedral crystals embedded in a crystalline limestone with associated pyrites, diopside, &c. Even the crystals themselves contain minute particles of these minerals as enclosures. The stone lapis-lazuli is this crystalline limestone containing varying amounts of the mineral lazurite. When this predominates we have the best

quality material, and when it is present in smaller amounts the stone is only a pale blue. The rock has been produced by the baking of an impure limestone near its contact with an intruded mass of molten granite. Such contact metamorphosed limestones or marble are of common occurrence, but only rarely do they contain just the right amounts of clayey matter, sodium, and sulphur for the formation of lapis-lazuli. Ultramarine is produced artificially by baking in a crucible a mixture of china-clay, sodium carbonate, charcoal, and sulphur. In the production of the natural stone an excess of sulphur was usually present, and this separated out as iron sulphide in the form of pyrites (iron-pyrites). This is often seen as bright yellow brassy specks embedded in the blue ground, suggesting a comparison with the deep blue sky bedecked with stars. The stone is also often splashed and veined with calcite which may be yellow from iron staining. Owing to the presence of those impurities, the specific gravity of the stone is very variable, ranging from 2.5 to 2.9. For the pure mineral lazurite the specific gravity is about 2.4. Lazurite is a complex alumino-silicate and sulphide of sodium. It is readily decomposed by hydrochloric acid, giving off a nasty smell of sulphuretted hydrogen.

The best quality of lapis-lazuli comes from Badakshan in the north-east corner of Afghanistan, in the same region as the ruby and red spinel, which also occur in a crystalline limestone. The mines were visited by Marco Polo and described by him in 1271. Material of a paler colour comes from the south-west shore of Lake Baikal in Siberia; and paler still, from the Andes in Chile. The stone is occasionally used as a ring-stone and beads, but is more often used for small ornaments and crosses. Thin slices are used for inlaying in boxes and table-tops. Common imitations of lapis-lazuli are now much sold under the names "Swiss lapis" and "German lapis". This is hornstone,

jasper, or chalcedony artificially stained a Berlin-blue colour with ferric ferrocyanide. These stones usually show small glassy specks of quartz, instead of the brassy specks of pyrites.

Other minerals closely related to lazurite and belonging to the same group of rock-forming minerals are haüyne and sodalite. Haüyne, which contains sodium sulphate in place of sodium sulphide, is found as bright blue crystals in Vesuvian lava. Sodalite, with sodium chloride in place of sulphide, occurs as large masses of a bright blue colour in nepheline-syenite, especially in Canada, and has been used as an ornamental stone.

TURQUOISE is supposed to derive its name from the fact that the stones were exported from Persia through Turkey; but the material has also come from Turkestan. Thomas Nicols, in 1652, has the term "Turkey stone". The colour ranges from sky-blue and pale blue to greenish blue and pale sea-green; and the lustre is vitreous to waxy. In American books the best colour is described as a robin's-egg blue, the American robin being a thrush. The colour of some material is liable to fade on exposure to light, and may be affected by grease, perspiration, and soap. In external appearance the material seems to be amorphous, but when thin sections are examined under the microscope it is seen to consist of an aggregate of minute crystals. Very small single crystals have recently been found in Virginia, and these on measurement proved to be triclinic. Chemically, turquoise is a hydrated phosphate of aluminium with variable amounts of copper (CuO 3-9%) and iron (Fe_2O_3 1-4%), and no satisfactory formula can be given. The blue colour is due to copper and the green to iron. Stones are cut in a cabochon form, and when mounted are often set round with small diamonds.

The best turquoise has long come from near Nishapur in the province of Khorasan, north-east Persia, where it occurs in crevices in a weathered volcanic rock (trachyte) of Tertiary age. Paler stones, which often fade when taken from the rock, occur as seams in sandstone at several places along the west coast of the Sinai peninsula. The mines here were worked by the ancient Egyptians, and used for carving as scarabs and other ornaments. Material of good quality is also found in New Mexico, Arizona, California, and Colorado, and worked articles are often to be found with prehistoric remains in Mexico and Central America.

Imitations of turquoise are easily made and have been rampant even since the time of the ancient Egyptians. Thomas Nicols (1652) writes:

The Venetians have a very pretty way by which they will neatly imitate this gemm, and that is with Venice glasse, prepared with a convenient skie-coloured tincture.

Imitations in material of the same chemical composition are made by subjecting precipitated aluminium phosphate coloured with copper under a high pressure. But this product does not show under the microscope the same structure as natural turquoise.

Odontolite or bone-turquoise is fossil bone or ivory stained naturally by copper solutions formed by the weathering of copper ores.

Variscite is another hydrated aluminium phosphate which is of an apple-green colour. It is found mostly in Utah and has been used as a gem-stone. Lazulite (not to be confused with lazurite) is a hydrated phosphate of aluminium, magnesium, and iron which forms monoclinic crystals of a good blue colour, and when cut often somewhat resembles turquoise.

KEY TO THE CHARACTERS OF LAPIS-LAZULI

Crystals, cubic, but usually as compact masses. Composition, $\text{Na}_5\text{Al}_3\text{S}_3(\text{SiO}_4)_3$, with admixture of other minerals. Specific gravity, 2.5–2.9 (for pure lazurite, 2.4). Hardness, $5\frac{1}{2}$. Refractive index of pure lazurite, 1.50. Opaque. Localities: Badakshan, Lake Baikal, Chile.

KEY TO THE CHARACTERS OF TURQUOISE

Crystals, triclinic, but always as compact masses. Composition, hydrated aluminium phosphate with copper and iron, $\text{H}_{18}\text{CuAl}_6\text{P}_4\text{O}_{29}$. Specific gravity, 2.6–2.8. Hardness, 6. Refractive indices, 1.61–1.65. Opaque. Localities: Persia, Sinai, Arizona, &c.

CHAPTER XXII

Miscellaneous Gem-stones

THERE are many minerals suitable for use as gem-stones. Some are so rare (much rarer than diamond!) that they are quite unknown in the jewellery trade; and others are so common that they are regarded as of little value. The following summary list of minerals that have been so used gives their main features; other details will be found in the reference lists at the ends of chapters of the general portion of this volume.

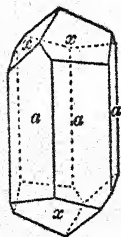


Fig. 56.—Crystal of Phenakite

PHENAKITE (fig. 56) is beryllium orthosilicate, Be_2SiO_4 . The colourless rhombohedral crystals much resemble those of quartz, but here the rhombohedron faces (x) are set askew over the hexagonal prism (a), and the prism faces are striated vertically. It is on account of its resemblance to quartz that the mineral receives its name, from *φῆναξ*, a cheat. Clear crystals, which have been cut as fine gems, are from the emerald mines in the Urals, and more recently from the gold mine of São Miguel de Piracicaba in Brazil.

EUCLASE is also a beryllium mineral, HBeAlSiO_5 , from the Urals and Brazil, where it is found as small monoclinic crystals, which possess a wonderfully perfect cleavage in one direction, hence the name. It is usually pale green, rarely emerald-green or sapphire-blue. A single large crystal of this rare mineral has recently

been found in the mica mines in Tanganyika Territory.

DIOPHASE, copper silicate, H_2CuSiO_4 , is found as brilliant emerald-green crystals in copper mines in Siberia and in French and Belgian Congo, but these are usually cloudy and fissured (even more so than emerald itself).

WILLEMITE, zinc silicate, Zn_2SiO_4 , is an abundant zinc ore at a few localities, but only at Franklin Furnace in New Jersey have clear pale yellow crystals been found.

ENSTATITE, BRONZITE, and HYPERSTHENE form an isomorphous series of orthorhombic pyroxenes of importance as rock-forming minerals. They are metasilicates $(Mg,Fe)SiO_3$ with varying proportions of magnesium and iron, the members of the olivine group being the corresponding orthosilicates. Enstatite, at the magnesium end of the series with only little iron, has been found as clear crystals of a bright green colour in the kimberlite of the diamond mines in South Africa. When cut it much resembles olivine. Bronzite, the next member in the series containing more iron, is bronze-yellow in colour with a sub-metallic sheen or lustre. Hypersthene, containing still more iron, is dark brown in colour with a more pronounced metallic lustre. The last two are sometimes cabochon cut.

DIOPSIDE, another rock-forming mineral of the pyroxene group, but monoclinic in crystallization, is occasionally found as clear crystals of a light or dark green colour. Crystals suitable for cutting have come from Zillertal, Tyrol.

SPODUMENE, so named on account of its usual ash-grey colour, is a silicate of lithium and aluminium, and large crystals up to ninety tons in weight have been mined from pegmatite in South Dakota as a source of lithium salts. Clear crystals of a rich emerald-green colour, and associated with emerald, are known only from Alexander County, North Carolina. This variety is called hiddenite, and is much rarer and more valuable than emerald. The nearest post office to where it is

found is now honoured with the name of Hiddenite. A beautiful violet or lilac-coloured variety called kunzite is found in pegmatite in San Diego County, California, and Madagascar, and shows a striking pleochroism. Yellow and blue crystals of gem quality have come from Brazil. The crystals have perfect cleavages in two directions, and must not be dropped.

RHODONITE has its name from $\rho\delta\delta\omicron\nu$, a rose, because of its characteristic pink colour due to the presence of manganese, it being a silicate of manganese, $MnSiO_3$. It is usually found as compact granular masses veined with black oxide of manganese and is used mainly as an ornamental stone. A block weighing forty-seven tons has been cut at Ekaterinburg in the Urals. Smaller clear crystals of a pink or brownish-red colour are found in Sweden.

ORTHOCLASE, or potash-felspar, is an important member of the felspar group of rock-forming minerals. Usually it is dull and opaque; but in the Alps it is found as clear and colourless crystals called adularia. Clear crystals of a lemon-yellow colour from Madagascar give attractive gems when cut. Moonstone is a well-known variety of this species. These crystals are clear or slightly cloudy, but when viewed on one direction they display on the surface a bluish milky reflection or sheen, which has been fancifully compared with the light of the moon. This reflection is from a certain plane in the crystal, and the cabochon-cut stones must have this plane as the base. Practically all moonstones come from Ceylon, but a few of dark blue colour come from Burma. Amazon-stone is a verdigris-green variety of another potash-felspar known as microcline, which differs from the monoclinic orthoclase in being triclinic.

OLIGOCLASE, a soda-lime-felspar, is sometimes found as clear colourless crystals which have been faceted. Sunstone, or aventurine felspar, is a variety enclosing minute scales of hæmatite giving it a spangled effect.

LABRADORITE is another soda-lime-felspar containing

more lime and less soda than oligoclase. It is a widely distributed rock-forming mineral, but specimens from Labrador and a few other places, though apparently dull and unattractive in appearance, when turned around in the light suddenly flash up with vivid colours—red, yellow, green, or blue. This is due to the interference of light waves from thin films (as in opal), the films here being minute scales of some other mineral enclosed in the felspar crystal parallel to a certain plane.

ANDALUSITE, one of the three aluminium silicates with the formula Al_2SiO_5 , is occasionally found as green or brown pebbles in the gem gravels of Brazil. These are remarkable for the strong pleochroism (fig. 21, p. 54). An opaque greyish andalusite containing regularly arranged black enclosures shows a well-marked black cross when the crystal is cut into slices, and is known as chialstolite or cross-stone. The polished slices are worn as charms.

KYANITE, also Al_2SiO_5 , forms triclinic crystals of bladed habit, and its name has reference to its blue colour. The crystals are remarkable for the wide differences in hardness on different faces and in different directions on the same face (p. 25).

FIBROLITE, also Al_2SiO_5 , crystallizing, like andalusite, in the orthorhombic system but with different angles, usually forms compact fibrous masses and has sometimes been mistaken for jade. Clear crystals of a pale-blue colour are of rare occurrence in Burma and Ceylon.

STAUROLITE, a complex alumino-silicate of iron and magnesium crystallizing in the orthorhombic system. It is occasionally found as clear reddish-brown crystals. The crystals are usually twinned, giving cross-shaped forms, and are sometimes worn as charms.

CORDIERITE, a complex alumino-silicate of magnesium and iron as orthorhombic crystals. It is usually of a deep blue colour and is remarkable for its very strong pleochroism (p. 53).

IDOCRASE, a complex alumino-silicate of calcium, &c.,

forms good tetragonal crystals; those from Vesuvius (vesuvianite) are a rich brown colour, while those from Ala in Piedmont are bright green. Massive idocrase found as large blocks in California is called californite, and resembles jade.

EPIDOTE, a complex alumino-silicate of calcium and iron forming monoclinic crystals of a brown or dark green colour with strong pleochroism. Material suitable for cutting is found in Untersulzbachthal, Salzburg.

SCAPOLITE, a complex alumino-silicate and chloride of calcium and sodium forming tetragonal crystals. Clear crystals of a honey-yellow colour have recently been found in Madagascar, Brazil, and Switzerland, and have yielded effective faceted stones. A pink variety with opalescent sheen from Burma has been cabochon cut.

POLLUCITE, alumino-silicate of the rare alkali metal caesium, as cubic crystals. Clear colourless material from Oxford County, Maine, has yielded a few faceted stones.

SERPENTINE, hydrated silicate of magnesium with some iron, $H_4Mg_3Si_2O_9$, never as distinct crystals. It is much used as an ornamental stone, and is sometimes translucent with a yellowish-green or green colour, then resembling jade.

DANBURITE, boro-silicate of calcium, $CaB_2Si_2O_8$, as orthorhombic crystals very similar in form to those of topaz, but without the perfect basal cleavage. Clear colourless crystals are found in Japan, and recently golden-yellow material resembling topaz has come from Madagascar, and pale yellow and colourless material from Burma.

AXINITE, boro-silicate of calcium and hydrogen, as triclinic crystals with a characteristic axe-like form and strong pleochroism. Clove-brown crystals from Dauphiné have been cut as gems.

KORNERUPINE, boro-silicate of aluminium and magnesium, orthorhombic in crystallization. Olive-green

material of gem quality has come from Madagascar and Ceylon.

DUMORTIERITE, boro-silicate of aluminium, orthorhombic, as compact masses of blue or violet colour and taking a good polish, from California.

SPHENE, silicate and titanate of calcium, CaSiTiO_5 . The name, from $\sigma\phi\eta\nu$, a wedge, has reference to the characteristic wedge-shaped habit of the monoclinic crystals. Greenish-yellow crystals are found in crevices in the gneissic rocks of the Swiss Alps, and when these are sufficiently clear and large enough they cut as magnificent gems with a brilliant lustre and a play of prismatic colours exceeding that of diamond; but unfortunately the stone is too soft for wear unless treated with care. The mineral is known as large brown crystals at some other localities, and there is a good chance that more gem-quality material remains to be found.

BENITOITE, silicate and titanate of barium, $\text{BaTi}(\text{SiO}_3)_3$, as rhombohedral crystals of peculiar habit (p. 42), is known only from San Benito County, California. It yields a fine sapphire-blue gem, but rather too soft for rough wear.

HAMBERGITE, a rare beryllium borate, recently found as large crystals in Madagascar, from which colourless gems have been cut.

RHODIZITE, a rare borate mineral containing aluminium, beryllium, caesium, &c., found as pale greenish and yellowish cubic crystals in Madagascar. The high degree of hardness (8 on the scale) is remarkable.

BERYLLONITE, phosphate of beryllium and sodium, of rare occurrence as colourless orthorhombic crystals in Maine, U.S.A.

APATITE, phosphate and fluoride of calcium, a common mineral of importance as a source of phosphate fertilizers, is sometimes found as clear crystals of various bright colours. Blue crystals from the ruby mines in Burma show a remarkable dichroism—sky-blue and pale yellow. The hardness is only 5 on the scale.

FLUORITE or FLUORSPAR, calcium fluoride, CaF_2 , as cubic crystals, showing a wide range of colours which cut as attractive stones but with a low degree of hardness (4). The "blue-john" variety, peculiar to Derbyshire, is carved as vases and various ornaments.

CASSITERITE, tin oxide, SnO_2 , as tetragonal crystals, the most important ore of tin, is rarely found as clear crystals of a yellow, brown, or red colour which cut as very brilliant gems.

HÆMATITE, iron oxide, Fe_2O_3 , as rhombohedral crystals, an important ore of iron. A compact form of kidney-iron-ore is cut to resemble black pearls.

RUTILE, titanium oxide, TiO_2 , as tetragonal crystals, is usually dark brown or black, but is very brilliant when cut, the refractive index being considerably higher than that of diamond. Spectacular gems ("titania") of a faint yellowish tint have recently been produced artificially by the Verneuil process.

ZINC-BLENDE or BLENDE, zinc sulphide, ZnS , the common ore of zinc, is found at Santander, Spain, as clear yellow cleavage masses which have been cut as lustrous gems with an optical dispersion greater than that of diamond, but the hardness ($3\frac{1}{2}$ -4) is very low. Small ruby-red crystals are found at some other localities.

CHAPTER XXIII

Gem Materials of Organic Origin: Amber, Jet, Pearls, Coral

THE materials remaining for this last chapter are neither stones nor minerals, but are of organic origin; and they are not taken very seriously by mineralogists. They are plant and animal products, and should be studied by botanists and zoologists.

AMBER is a fossil resin. It is found as pebbles or masses of irregular shape, rarely as tear-shaped drops, in beds of sand and clay that were deposited during the Tertiary period of geology. Compared with the majority of the gem-stones previously considered, amber is of comparatively recent origin; but collectors, who like to have their amber really old, may rest assured that it is (if genuine) at least ten million years old, or perhaps rather more. From a study of the remains of plants and animals, principally insects, often to be seen embedded in amber, palæontologists are able to tell something about the life at that period. The resin, which in a soft and sticky state entrapped the insects, was exuded by a pine tree, now extinct, which palæobotanists call *Pinus succinifera*, succinum being the Latin name for amber.

Amber varies considerably in appearance and quality; and for this reason it is not always easy to distinguish it from other forms of resin and the many artificial imitations. It may range from pale yellow or almost colourless through "amber-yellow" to reddish, dark

brown, and almost black; and greenish and bluish tinges are sometimes shown. It may range from clear and transparent to cloudy and opaque. The chemical composition is also variable, approximating to the formula $C_{10}H_{16}O$, but some sulphur is also present, and it is not a simple chemical compound. When heated it gives off oil of amber and succinic acid, and with different solvents at least four different kinds of resin can be extracted. To be really sure that a material is amber it must be tested chemically. A popular idea of a reliable test for amber is that it becomes electrified when rubbed, then attracting bits of paper. All things, even one's hands, develop electricity when rubbed, but unless the material is a bad conductor, the charge immediately escapes. Bad conductors must be used in all electrical fittings, though amber is not used for this purpose; and these as well as all imitation amber will answer to the same test. However, this property was first observed in amber, the word electricity being derived from the Greek name, *ἤλεκτρον*, electron, for amber.

The most important source of amber is in East Prussia along the Baltic coast, the centre of the amber industry being at Königsberg; and material from there is usually distinguished as Baltic amber. The amber-bearing beds are worked in open pits and also by underground mining at Palmnicken. The beds also extend under the sea, and after storms much amber is collected on the beach and dredged from the sea. Pieces may be occasionally collected along the beach away to the east, even as far as the English coast between Essex and Yorkshire. Other amber localities of lesser importance are in Upper Burma, Sicily, and Romania. The Burmese amber, or burmite, is mined in the Hukawng valley in the Myitkyina district, not far from the jadeite mines. It is of a darker reddish-brown colour and is largely exported to China.

Copal is a fossil resin of more recent origin than

amber, and it is usually lighter in colour and clearer. This includes the Zanzibar copal and the Kauri-gum of New Zealand, which are dug from the surface soil. Imitations of amber are very frequently made. Yellow glass is at once distinguished by its weight; celluloid by the way it can be pared with a knife; and bakelite by its slightly higher specific gravity. In salt water (three or four teaspoonfuls of salt in a tumbler of water) amber (specific gravity 1.05-1.1) will float, while bakelite (1.25) will sink. In ultra-violet rays amber displays a greenish fluorescence, which is not shown by artificial imitations.

JET is a fossil wood, and really a form of coal. It is found as logs representing tree trunks in shales of Liassic age on the Yorkshire coast in the neighbourhood of Whitby. Most of the jet now cut there is, however, imported from Asturia in Spain. The material is "jet-black" and takes a good polish. The Scotch cannel-coal is not a bad substitute.

PEARLS. A quaint account, worth quoting, is given by Camillus Leonardus in his *Speculum Lapidum* (Venetia, 1502), English translation *The Mirror of Stones* (London, 1750):

Margarita, or Pearl, has the first Place among white Gems, generated by celestial Dew in some Sea Shell Fish, as is held by Authors. These Shell-Fish, it's reported, early in a Morning, at a certain Season of the Year, leave the Bottom of the Sea, to draw in the Air, of which Pearls are generated; and according to the Clearness of the Air taken in, the Pearls are either lucid or muddy. The Pearl is for the most part round, and by some is called an *Onion*.

Pearls are malformations of the external skeleton of the pearl-oyster (*Meleagrina margaritifera*), and with the shell itself they are secreted by the mantle of the mollusc. They consist of the same material and with the same structure as the mother-of-pearl that forms the inner side of the shell. When they are found attached to the shell they have the irregular shape of

"button" or "blister" pearls; while those found isolated and embedded in the tissue of the mantle are spherical. Some foreign matter—a grain of sand or even a small crab or fish—has accidentally got inside between the mantle and the shell; and to allay the irritation the mollusc has encased the object in nacreous material. The isolated pearls in the mantle are due to the intrusion of parasitic worms. The tomb of a parasitic worm is not a really pleasant object with which to bedeck a fair neck.

The nacreous material of pearls and also of mother-of-pearl consists of alternate layers of calcium carbonate (about 88%) and horny substance (conchiolin) arranged parallel to the surface. A spherical pearl is therefore built up like an onion. As seen in thin sections under the microscope, the calcium carbonate forms a series of little overlapping plates or scales, each built up of a multitude of minute needle-like crystals arranged perpendicular to the surface. These are crystals of aragonite, a mineral differing from calcite in the orthorhombic form of its crystals. This finely laminated structure is the cause of the characteristic pearly lustre (which is also shown by crystals possessing a very perfect cleavage in one direction); and also for the play of rather confused prismatic colours produced by the interference of light at the surfaces of the laminæ.

The principal pearl fisheries are in several parts of the Indian Ocean, off the coasts of Ceylon and Western Australia, Persian Gulf, &c. Pearls are also obtained off the Central American coast and in the West Indies, and in the Pacific Ocean, but not in all cases from the typical pearl-oyster. Pearls are also found in the fresh-water mollusc *Unio* in Scotland and North America.

Since pearls are the result of a morbid condition of the mollusc, it is possible to stimulate their formation and growth by artificial means. The result is the same, and it matters little whether the source of the irritation has been accidentally swallowed by the oyster itself,

poked in by a mischievous boy, or skilfully introduced by an ingenious Jap. This has been practised in China on fresh-water mussels since the thirteenth century, Buddha images on the inside of shells being well known. More recently, as a result of zoological research, it has been possible by a surgical operation to introduce the foreign object within a fold in the mantle of the mollusc. Since 1921 these so-called "cultured" pearls have been produced in large quantities, much to the dismay of pearl merchants.

Pearl-oysters have a life of 11-12 years. The operation is performed on young individuals, the object

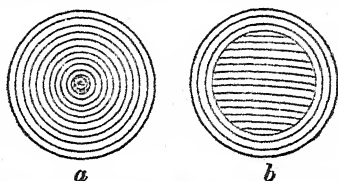


Fig. 57.—Cross-sections of (a) a natural pearl; and (b) a "cultured" pearl

introduced being a cut sphere of mother-of-pearl, and they are then kept in baskets suspended in the sea for about seven years, when a nacreous layer about one millimetre in thickness is formed. Such a "cultured" pearl has the structure shown in cross-section in fig. 57 *b*, while a wholly natural pearl (fig. 57 *a*) has a concentric structure up to the centre. To ordinary inspection the two are indistinguishable. With a bead, they can be distinguished by inserting a pair of tiny mirrors along the bore. With an unbored pearl, an X-ray Laue photograph will show a distinction. Since the minute aragonite prisms are arranged perpendicular to the concentric layers, *b* will show the same pattern as *a* only in a single direction. If the foreign object is a small or seed pearl, then both these methods fail. Imitation pearls consisting of hollow glass beads with a special filling are easily recognized—except at a distance.

CORAL. Here Leonardus (1502) is again instructive:

Coral grows in the sea like a Tree, but without Leaves, in Magnitude not exceeding two Feet. Of this there are two Species, the Red and White; tho' *Avicen* holds there is a third Species, which is Black. I once saw the White and Red join'd on one Stem. The White indeed is often perforated, and are good for nothing; but those which are perfectly white, and the reddest, are the best. Their Virtues, but chiefly of the Red, is to stop every Flux of Blood. Being carried about one, or wherever it be in a House or Ship, it drives away Ghosts, Hobgoblins, Illusions, Dreams, Lightnings, Winds and Tempests.

This is the axial skeleton of a colony of coral polyps, *Corallium rubrum*, belonging to the same group of animals as the common sea-anemone. It consists of calcium carbonate (about 85%) in the form of the mineral calcite, together with some magnesium carbonate, iron oxide, &c. It is found in the Mediterranean, and the working of coral is entirely an Italian industry. Material of the best rose-pink colour fetches a high price.

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